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ფაკულტეტი

**ივანე პეტოევი**

**სადისერტაციო ნაშრომი**

**periodul i structurebis el eqtrodinamikuri**

**Tvisebebis Seswavi a zogierTi kompl eqsuri masal ebis**

**Tvisebebis misaRwevad**

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## Sesaval i

### K

**probl emis aqtual oba.** Tanamedrove cifruli da anal oguri el eqtronuli mowyobil obebi (kompiuterebi, mobiluri kavSirgabmul obis mowyobil obebi da a. S.) mnisvnel ovan rols asrul eben sazogadoebriv cxovrebaSi. maT gareSe warmoudgenelia Tanamedrove medicinis, sakomunikacio sistemebis, sabanko sektoris da sxva dargebis ganvitareba.

cifruli da anal oguri sistemebis ganvitarebis tendenciebi miutitebs imaze, rom maTi momaval i samusao sixsireebis diapazoni ufro da ufro mikrotal Rur (terahrcul da infrawitel) areSi gadaiwevs. am diapazonSi standartuli masal ebi (naxevargantarebi da metaluri zedapirebi) gansxvavebul Tvisebebs avl enen, kerZod isini metad STantqaven am sixsiris tal Rebs an xdebian rTul ad dasamuSavebel i. amis gamo maTi gamoyeneba mnisvnel ovnad SezRudulia. amitom aqtualuri gaxda axali masal ebis, struqturebis da midgomebis Zieba. am masal ebs zogadad kompl eqsuri masal ebi da aseve metamasal ebi ewodebaT.

rogorc CvenTvis cnobilia, istoriul ad kompl eqsur masal ebze moTxovnil eba egreT wodebuli "stel sis" amocanidan daiwyo, rodesac miznad iyo dasaxuli Seqmnil iyo dafena minimaluri gabnevis ganivkveTIT, ris Sedegadac igi ucinars gaxdida radarebiTvis samxedro TviTmfrinavebs.

kompl eqsuri masal ebi, zogadad, warmoadgenen xel ovrur nivTierebebs, romel Ta el eqtromagnituri Tvisebebi gansxvavdeba maTi Semadgenel i nivTierebebis el eqtromagnituri Tvisebebisgan.

kompl eqsuri masal ebis bazaze, kerZod, Sesaziebel ia damzaddes aRniSnul sixsirul diapazonSi momuSave l ogikuri da integraluri sqemebi, aseve sxvadasxva el eqtronuli mowyobil obebi, magal iTad: sixsiruli fil tri, cirkul atori, simZl avreTa gamyofi, simZl avreTa Semrevi, tal Rgamtari, aseve antenuri struqturebi, rogoricaa mimarTuli gamosxivebis mqone antena egreTwodebuli fazirebuli antena roml is gamosxivebis mimarTul eba SegviZlia vcvaloT el eqtronul ad. metamasal ebis gamoyeneba am miznit dRes dReobit metad aqtualuria, radgan Tanamedrove el eqtronuli mowyobil obebis gadasvla maRal sixsirul diapazonSi arsebuli Zveli teqnologi ebis bazaze rTulia da zog SemTxvevaSi SeuZiebel i maTi zomebis Semicirebis gamo. Tanamedrove teqnologiis gamoyenebit kompl eqsuri masal ebis damzadeba Sedarebit martivia da is ar aris SezRuduli sixsiruli diapazoniT.

unda aRiniSnos, rom arsebobs bunebrivi kompl eqsuri masal ebi. magal iTad, bunebrivi kiraluri garemo, romel ic iyo cnobili jer kidev XIX saukunis dasawyisidan. termini "kiraluri" pirvel ad gamoyenebuli iqna uil iam tomsonis mier da niSnavs obieqtis SeuTavsebl obas mis sarkul anarekl Tan - aranairi brunviti da gadataniTi moZraobebiT. bunebriv kiralur obieqtebs warmoadgenen Saqris, aminomJavebis, dnm-s da organuli polimerebis mol ekul ebi (<http://www.complex.mat.ethz.ch>). rogorc wesi, bunebriv kompl eqsur masal ebs ar gaaCniat sasurvel sixsirul diapazonSi praqtikisaTvis saWiro Tvisebebi. amis gamo, zogadad, maTi gamoyeneba praqtikaSi SeuZiebel ia. amitomac arsebobs maTi xel ovrurad miRebis didi moTxovnil eba.

zogadad cnobil ia, rom xel ovnuri kompl eqsuri masal a SeiZl eba Sei qmnas Tu Cveul ebriv diel eqtrikSi SeviyanT gamtari el ementebisagan Semdgar samganzomil ebian periodul mesers [1-6].

Tanamedrove teqno logiis ganviTarebiT SesaZl o gaxda kompl eqsuri masal ebis damzadeba. unda aRiniSnos, rom aseTi teqno logiebi saqarTvel oSic arsebobs. ital iel ebTan, amerikel ebTan da espanel ebTan TanamSroml obiT, mimdinareobs Txevadi kristal ebis el eqtromagnituri Tvisebebis gamokvl eva optikur diapazonSi, real uri eqsperimentebis saSual ebiT [7-16]. kerZod, interess warmoadgens optikur diapazonSi momuSave gadawyobadi organzomil ebiani da samganzomil ebiani fotonuri kristal ebis miReba Txevadi kristal ebis bazaze.

rogorc cnobil ia, fotonuri kristal i warmoadgens periodul mesers, roml is periodi tal Ris sigrZis rigisaa. el eqtromagnituri tal Ris gavrcel eba aseT kristal Si Seesabameba el eqtronis gavrcel ebas naxevar gamtarSi. maqsvel is gantol ebebis amonaxsni fotonur kristal ebisaTvis aCvenebs rom arsebobs tal Ris sigrZis iseTi mniSvel obebi, rodesac maTSi tal Ris gavrcel eba ar xdeba. gadawyobadi fotonuri kristal i warmoadgens iseT fotonur kristal s, roml is konfiguracia SeiZl eba Sei cval os gare el eqtromagnituri vel is zemoqmedebiT. aseTi saxis fotonuri kristal ebi did gamoyenebas poul oben optikuri kavSir gabmul obis sistemebSi.

**kvl evis obieqti da amocanebi.** rogorc cnobil ia, standatrul i masal ebi, rogoricaa gamtarebi, diel eqtrikebi da naxevarad gamtarebi, aRiwerebian zogadad ori parametris saSual ebiT: diel eqtrikul i  $\epsilon$  da magnituri  $\mu$  SeRwevadobebiT.

erTgvarovan izotropul diel eqtrikis SemTxvevaSi am parametrebs gaaCniaT namdvil i mniSvel obebi. maT SeiZl eba gaaCndeT aseve kompl eqsuri mniSvel obebi, rasac aqvs adgil i, magal iTad danakargebis mqone garemoSi. zogadad, anizotropul i garemos SemTxvevaSi, diel eqtrikul i da magnituri SeRwevadobebi warmoadgenen tenzorul sididebs, magal iTad pl azmis da damagnitebul i feritis SemTxvevaSi. aseT garemoSi kavSiri induqciis veqtorebsa da daZabul obis veqtorebs Soris Semdegi saxiT Caiwereba:

$$D_i = \epsilon_{ij} E_j, \quad B_i = \mu_{ij} H_j.$$

CamoTvl il i masal ebisagan gansxvavebiT kompl eqsuri masal ebis aRwera moiTxovs kidev damatebiT or  $\alpha$ ,  $\beta$  parametrs, romel Tac admitansebi ewodebaT. gasagebia zogadad, rom am oTxive parametrs aseve tenzorul i buneba SeiZl eba gaaCndeT. aseT rTul garemos bianizotropul i kompl eqsuri garemo ewodeba. am SemTxvevaSi zemoaRniSnul i kavSiri gamoisaxeba rogorc

$$D_i = \epsilon_{ij} E_j + \alpha_{ij} H_j, \quad B_i = \mu_{ij} H_j + \beta_{ij} E_j.$$

kerZo SemTxvevas warmoadgens biizotropul i garemos, romel Sic oTxive parametrs namdvil i mniSvel obebi gaaCniaT. am damatebiT admitansebeza damokidebul i is saintereso Tvisebebi, romel nic kompl eqsur masal ebs gaaCniaT.

warmodgenil naSromSi ganxil eba, droSi harmoniul i el eqtromagnituri tal Ris difraqciisa da gabnevis amocanebi zogierT

metal o - diel eqtrikul struqturbze. ganxil eba aseTi struqturbis sasrul i da usasrul o SemTxvevebi. Zogadad, struqtura warmoadgens periodul mesers, romelic moTavsebul ia diel eqtrikSi. meseri Sedgeba mcire el eqtrul i zomebis mqone gamtar el ementebisagan, roml ebsac garkveul sixSireebze rezonansul i Tvisebebi gaaCniaT. Cveni amocanaa, aseTi sistemebis el eqtrodinamikuri Tvisebebis Seswavl a rezonansul sixSireebis areSi, rodesac isini kompl eqsuri garemos Tvisebebs izenen.

cnobil ia, rom yovel rezonansul sixSireze TviToeul el ementze aRZrul i denis amplituda mkveTrad izrdeba. dasawyisSi, maRal i vargisianobis Sedegad rezonansul sixSireze, sistema izens dacemul i tal Ris energiis did nawils da procesis damyarebis Semdeg srul ad gadasxivdeba. am dros, sixSiris zrdisas, yovel ganmxol oebul el ementsac ki ucdeba axal i miul evadi speqtral uri komponenti, rac acens Sori zonis diagramaSi axal foTols. rodesac gvaqvs aseTi el ementebis erTobl ioba meserSi, maTi el eqtrodinamikuri urTierTqmedeba ansambl Si izrdeba da iwvevs denis kidev ufro met gazrdas yovel el ementze. aRniSnul i urTierTqmedeba damokidebul ia agreTve el ementebis Soris manZil ze, radgan igi gansazRvravs urTierTqmedebis energiis fazas. el ementebis Soris manZil i aseve SeiZl eba iyos rezonansul i. aseT movl enas SeiZl eba vuwodoT ormagi rezonansi. rodesac sistema moTavsebul ia diel eqtrikSi, moiZebneba srul i sistemis iseTi parametrebi, rodesac aRniSnul i efeqtebi mkveTrad izrdeba da am dros igi izens kompl eqsuri garemos Tvisebebs.

mesris el ementis geometriul i forma gansazRvravs, romel tipis kompl eqsur garemos Seesabameba aRebul i struqtura mis rezonansul sixSireebze. kerZod, marjvena an marcxena kiral obis mqone el ementebis struqtura diel eqtrikSi Seesabameba kiral ur garemos; Tu mesris el ementi warmoadgens koncentrirebul or Ria rgols, maSin garkveul sixSireebze Sesabamis garemos uaryofiTi gardatexis maCvenebel i gaaCnia da a. S.

zogadad, metad sasurvel ia naSromSi ganxil ul i struqturbis siRrmiseul i Seswavl a im mizniT, rom SevZl oT imis dadgena, Tu konkretul ad romel kompl eqsur garemos Seesabamebian isini da risi tolia maTi el eqtrodinamikuri parametrebis (SeRwevadobebis da admitansebis) mniSvnel obebi. es mogvcems saSual ebas SemdgomSi amovxsnaT Sebrunebul i amocana da kompiuterul i model irebis saSual ebiT davamodel iroT sasurvel i parametrebis da Tvisebebis mqone kompl eqsuri masal a. unda aRiniSnos, rom aseTi amocanis gadaWra dResdReobiT metad rTul probl emas warmoadgens. saqme imaSia, rom el ementebis periodul i wyoba diel eqtrikSi qmnis miRebul i struqturis anizotropias, ris gamoc misi oTxive el eqtrodinamikuri parametri tenzorul xasiaTs izens. Sesabamisad izrdeba ucnobi parametrebis raodenoba, romelic am SemTxvevaSi, zogadad aris  $4 \times 3 \times 3 = 36$ . gamosaval i aseT rTul SemTxvevidan SeiZl eba iyos, Tu davarRvevT el ementebis periodul obas diel eqtrikSi, ise rom yovel maTgans damoukidebel i orientacia da mdebareoba gaaCndes. maSin maTi raodenobis gazrdis Sedegad SesaZl oa saZiebel i el eqtrodinamikuri parametrebis gasaSval oeba. zogadad damtkicebul ia, rom aseTi saxis struqtura unda Seesabamebodes biizotropul kompl eqsur garemos, romel Sic kavSiri induqciis da daZabul obis veqtorebs Soris SedarebiT ufro martivad gamoisaxeba:

$$\vec{D} = (\varepsilon + \mu\alpha\beta)\vec{E} + i\mu\alpha\vec{H}, \quad \vec{B} = -i\mu\beta\vec{E} + \mu\vec{H}.$$

kerZo SemTxvevaSi, Tu srul deba piroba  $\alpha = -\beta$  maSin garemos tel egenis garem o ewodeba. Tu  $\alpha = \beta \neq 0$ , maSin garemos kiral uri Tvisebebi gaaCnia.

miuxedavad aseTi gamartivebisa, am SemTxvevaSi Cndeba axal i probl ema. saqme imaSia, rom el ementebis raodenobis aseTi gazrda iTxovs ricxviTi gamoTvl ebis dros metismetad did kompiuterul resursebs.

**kvl evis mizani.** kompl eqsuri masal ebis el eqtrodinamikis ZiriTadi mizani, praqtikis Tval sazrisiT, mdgomareobs:

1. xel ovnuri kompl eqsuri masal ebis Tvisebebis Seswavl aSi, maTi praqtikaSi gamoyenebis mizniT.

2. imis dadgenaSi Tu ramdenad SesaZl ebel ia sasurvel i Tvisebebis mqone kompl eqsuri masal ebis damzadeba, romel nic imuSaveben sasurvel sixSirul diapazonSi.

mocemul i sadisertacio naSromi wamroadgens erTerT etaps am zogadi miznebis misaRwevad. masSi ganxil eba ramodenime saxis metal o-diel eqtrikul i struqtura da xdeba maTi Teoriul i analizi. Semdeg, kompiuterul i model irebis saSual ebiT xdeba maTi Tvisebebis (kiral oba, uaryofiTi gardatexa da a. S.) gamokvl eva.

kompiuterul i model ireba da ricxviTi eqsperimentebi win unda uZRvodes real ur eqsperiments, sistemis optimal uri parametrebis dasadgenad. amasTanave aseTi ricxviTi eqsperimenti aris bevrad ufro advil i, moxerxebul i da ar aris dakavSirebul i did xarj ebTan.

unda aRiniSnos rom am mimarTul ebiT muSaobisas miRebul i Sedegebi aprobaciis mizniT wardgenil iqna samsj el od konferenciebze MMET 2010, DIPED 2012 da maT dadebiTi Sefaseba daimsaxures. amis Semdeg aRniSnul i Sromebi miRebul iqna dasabeWdad Jurnal Si "Journal of Communications Technology and Electronics" da aseve saberZneTSi, Jurnal Si "Journal of Applied Electromagnetism".

**probl emis Tanamedrove mdgomareoba.** 1967 wel s viqtor vesel agom gamoaqveyna Sroma, romel Sic aRniSna, rom Tu garemos el eqtrul da magnitur SeRwevadobebis gaaCniaT uaryofiTi mniSvnel obebi, maSin aseT nivTierebas eqneba uaryofiTi gardatexis maCvenebi i [17]. marTI ac, Tu ganvmartavT gardatexis koeficients rogorc  $n = \sqrt{\varepsilon}\sqrt{\mu}$  da davuSvebT, rom  $\varepsilon = -\varepsilon'$ ,  $\mu = -\mu'$ , maSin miviRebT  $n = \sqrt{-\varepsilon'}\sqrt{-\mu'} = i^2\sqrt{\varepsilon'}\sqrt{\mu'} = -n'$ . aseT garem oSi tal Ris el eqtrul i, magnituri da gavrcel ebis mimarTul ebis veqtorebi qmnian marcxena brunvis sistemas. pirvel i uaryofiT indeqsiani nivTiereba Seiqmna 30 wl iT gvian, mas Semdeg rac smitma Seqmna rezonatorul i meseri.

dResdReobiT radiofizikaSi sul ufro da ufro did interest iwvevs aseTi struqtorebis da zogadad, kompl eqsuri masal ebis gamoyeneba, radgan maTi saSual ebiT SeiZl eba unikal uri Tvisebebis mqone sistemebis Seqmna. kerZod, did interest iwvevs iseTi sistemebis Seqmna romel nic iyeneben bianizotropul i da kiral uri garem oebis Tvisebebs. kiral uri masal ebis Teoriul i gamokvl eva maTematikuri fizikis meTodebiT wamroadgens metad mniSvnel ovan da saintereso amocanas. SeiZl eba gamoyofil iqnas aseTi amocanebis ori kl asi: 1. speqtral uri amocanebi,

rodesac gamosakvl evia kiral uri masal ebis bazaze miRebul i rezonatorul i sistemebi. 2. aRznebis sawyis-sasazRvro amocanebi, roml ebSic Seiswavl eba kiral uri masal ebis bazaze Seqmnil i sxvadasxva tal Rgamtari sistemebis aRznebis procesebi da el eqtromagnituri tal Rebis gavrcel eba aseT sistemebSi.

zogadad, kompl eqsuri masal ebis el eqtrodinamikaSi SeiZl eba gamoyofil iqnas ori ZiriTadi amocana: 1. Sebrunebul i amocana, rodesac moiTxoveba xel ovnurad iqnas miRebul i sasurvel i el eqtrodinamikuri parametrebis (SeRwevadobebis da admitansebis) mqone struqtura. 2. pirdapiri amocana, romel ic mdgomareobs imaSi, rom struqturaze difraqciis da gabnevis amocanis amoxsnis safuZvel ze dadgindes misi, rogorc kompl eqsuri masal is el eqtromagnituri Tvisebebi (kiral oba, uaryofiTi gardatexa da a. S.).

CvenTvis cnobil ia msofi ioSi ramodenime j gufi, romel nic atareben Teoriul da eqsperimental ur kvl evebs ganxil ul dargSi. kerZod, arsebobs aseTi j gufi fineTSi - hel sinkis teqnol ogiur univesitetSi, kanadaSi [2], bel orusiaSi [3], SveicariaSi, SvedeTSi [4], ruseTSi - peterburgis teqnukur univesitetSi, moskovSi, radioteqnikis da el eqtronikis institutSi [18, 19], aSS - pensil vaniis univesitetSi [1, 20-39], arsebobs aseve j gufebi ingl isSi, safrangeTSi, da germaniaSi.

miuxedavad imisa, rom kompl eqsuri masal ebis gamokvl eva gamoyenebiT el eqtrodinamikaSi ukve aTvl eul s aRwevs, dRemde ar arsebobs dasrul ebul i Sesabamisi analitikuri Teoria, ris gamoc aseTi struqturabis gamokvl eva xdeba ricxviTi meTodebiT gamoTvl iTi fizikis da kompiuterul i model irebis saSual ebiT.

**Catarebul i kvl evis siaxl e.** sadisertacio naSromis siaxl es warmoadgens:

1. damxmare gamomxivebl ebis meTodis ganviTareba da misi gamoyeneba sxvadasxva metal o-diel eqtrikul i struqturabis gamosakvl evad. usasrul o periodul i struqturabis SemTxvevaSi miRebul ia periodul i grinis funqcia, romel ic am SemTxvevaSi damxmare gamomxivebel is vel is rol s asrul ebs.

2. Seqmnil i programul i paketi, romel Sic arsebobs ramodenime saxis mesris el ementis da diel eqtrikis formis SerCevis saSual eba. programaSi arsebobs SesaZl ebl oba vcval oT struqturis rogorc geometriul i parametrebis, aseve diel eqtrikis SeRwevadobebi. amasTanave, paral el urad mowmdeba TviT al goriTmis sizuste. maSasadame SesaZl oa sakmaod farTo kl asis metal o-diel eqtrikul i struqturabis model is Seqmna da maTi testireba winaswar arCeul i sizustiT.

Seqmnil i programul i paketi warmoadgens rogorc saswavl o, aseve samecniero saSual ebas. rogorc saswavl o saSual eba, igi xel s Seuwyobs aRniSnul i TematikIT dainteresebul studentebis intuiiciis gamomuSavebaSi, codnis miRebasa da ganmtkicebaSi. rogorc samecniero saSual eba, igi daexmareba am dargSi momuSave yvel a mecniers metal o-diel eqtrikul i struqturabis Tvisebebis Seswavl aSi da maTi parametrebis optimizaciSi. amasTanave, igi SeiZl eba wardgenil iqnas sxva univesitetebSi da samecniero kvl eviT institutebSi

3. kasinis el ementis ganxil va. naSromSi Seswavl il ia eqvsi gansxvavebul i formis mesris el ementi. esenia: gamtari monakveTi, gamtari Ria rgol i, ori gamtari koncentrirebul i Ria rgol i, gamtari spiral i, gamtari  $\Omega$ - el ementi da gamtari kasinis el ementi. naSromSi [30] ganxil ul iqna tal Rgamtarul i amocana, rodesac tal Rgamtaris ganivi kveTi kasinis oval s warmoadgens. kasinis el ementis ganxil va kompl eqsuri garemos model irebis mizniT, warmoadgens sadisertacio naSromis erTerT siaxl es, radgan rogorc CvenTvis cnobil ia, igi am mizniT araa gamoyenebul i sxva mkvl evarTa mier. am el ementis gamokvl evam gviCvena, rom mas gaaCnia rezonansul i Tvissebi farTo sixSirul diapazonSi da amitom mis bazaze miRebul struqturas aseve unda gaaCndes kompl eqsuri Tvissebi sixSireebis farTo areSi.

**kvl evis ZiriTadi ricxviTi meTodi.** maTematikuri fizikis mraval i amocana daiyvaneba wrfiv araerTgvarovan diferencial ur gantol ebamde kerZo warmoebul ebSi. aseTi gantol eba zogadi operatorul i saxiT Caiwereba rogorc

$$\hat{L}f(x) = g(x),$$

sadac  $\hat{L}$  warmoadgens wrfiv operators, xolo  $g(x)$  - cnobil funqcias. fizikurad, es gantol eba Seesabameba ucnobi  $f(x)$  vel is povnas, rodesac cnobil ia misi wyaroebis  $g(x)$  ganawil eba raime ( $D$ ) areSi.

rogorc cnobil ia, am gantol ebis zogadi amonaxsni SeiZl eba gamosaxul iqnas Sesabamisi grinis funqciis saSual ebiT, romel ic akmayofil ebs gantol ebas

$$\hat{L}G(x, y) = \delta(x - y),$$

sadac  $\delta$  del ta funqciaa. grinis funqcia Tavisi fizikuri azriT aris wertil ovani wyaros mier Seqmnil i vel i. sawyisi gantol ebis aRniSnul i amonaxsni Caiwereba rogorc

$$f(x) = \int_{(D)} G(x, y)g(y)dy.$$

grinis funqciis konkretul i saxe damokidebul ia sasazRvro da aseve damatebiT pirobebze. el eqtrodinamikis, hidroaerodinamikis, drekadobis Teoriis da fizikis sxva amocanebSi ucnobia pirvel rigSi TviT wyaroebis  $g(x)$  ganawil eba. es ucnobi ganawil eba SeiZl eba gamowveul iqnas, kerZod, cnobil i  $\varphi(x)$  zemoqmedebiT (aRznebiT). naTqvams aqvs adgil i, magal iTad droSi harmoniul i el eqtromagnituri da akustikuri tal Rebis difraqciis amocanebisaTvis sxvadasxva obieqtebze. am SemTxvevaSi  $\varphi(x)$  aRzneba dagemul tal Ras warmoadgens. amocana ixsneba Semdegnairad: daSvebul ia rom  $g(y)$  ganawil eba cnobil ia da iwereba ucnobi gabneul i  $f(x)$  vel is zogadi gamosaxul eba

$$f(x) = \int_{(T)} G(x, y)g(y)dy.$$



aq  $(\Gamma)$  gambnevi obieqtis zedapiria. iwereba aseve sasazRvro piroba romel sac unda akmayofil ebdes saZiebel i vel i dacemul vel Tan erTad  $(\Gamma)$  zedapirze:

$$\hat{W}(f(x) + \varphi(x)) \Big|_{x \in (\Gamma)} = 0.$$

aq  $\hat{W}$  sasazRvro pirobis operatoria. Tu CavsvavT  $f(x)$  funqciis gamosaxul ebas am sasazRvro pirobaSi, maSin ucnobi  $g(y)$  ganawil ebis mimarT miviRebT integral ur gantol ebas

$$\int_{(\Gamma)} \hat{W}G(x, y) \Big|_{x \in (\Gamma)} g(y) dy = -\hat{W}\varphi(x) \Big|_{x \in (\Gamma)}.$$

grinis funqcias  $(\Gamma)$  zedapize singul aroba gaaCnia, ris gamoc es integral uri gantol eba aseve singul arul ia.

imisaTvis rom Tavi avaridoT am singul arobas, momentebis meTodi gvTavazobs moyvanil i gantol ebis marcxena mxareSi arsebul i integral is Canacvl ebas wyaroebis diskretul i raodenobis jamiT, Tumca am SemTxvevaSi, sasazRvro piroba zedapiris yvel a wertil Si ar srul deba, rac iwvevs amonaxsnSi did cdomil ebas.

v. kupraZis mier SemoTavazebul iqna singul arobebis acil ebis al ternatiul i meTodi [31]. am meTodis saSual ebiT srul iad ixzneba singul arobis arsebobis probl ema  $(\Gamma)$  zedapirze, ris gamoc misi gamoyeneba bevrad ufro efeqturia. zogadi maTematikuri interpretaciidan gamomdinare [32], dgm mdgomareobs SemdegSi: kvl av ganvixil oT  $f(x)$  funqciis gamosaxul eba da warmovidginoT igi Semdegi miaxl oebul i mwkrivis saxiT

$$f(x) = \int_{(\Gamma)} G(x, y) g(y) dy \approx \sum_{n=1}^N g(y_n) dy_n G(x, y_n) = \sum_{n=1}^N a_n G(x, y_n),$$

sadac SemoRebul ia aRniSvna  $a_n = g(y_n) dy_n$  es mwkrivi warmoadgens sawyisi  $f(x)$  funqciis gaSl as grinis funqciebiT sxvadasxva  $y_n$  argumentebisTvis da  $N$  s gazrdiT misi sizuste izrdeba.  $G(x, y_n)$  funqciebis erTobl ioba, rodesac  $n=1, 2, \dots$ , qmnis srul wrfivad damoukidebel sistemas l ebegis  $L^2$  sivrceSi. v. kupraZis mier damtkicebul iqna, rom  $f(x)$  funqcia, rogorc gabneul i vel i, anal izuria da SeiZl eba misi anal izuri gagrZel eba  $(\Gamma)$  zedapiridan. es iZl eva saSual ebas wavanacvl oT  $y_n$  wertil ebis zedapiri  $(\Gamma)$  zedapiridan garkveul i  $d$  manZil iT. am wanacvl ebul  $y_n + d$  zedapirs damxmare zedapiri ewodeba, xol o masze ganl agebul wertil ovan  $a_n G(x, y_n)$  wyaroebis - damxmare gamomsxivebl ebi. maSasadame moyvanil i mwkrivis magivrad SegviZl ia ganvixil oT mwkrivi

$$f(x) = \sum_{n=1}^N a_n G(x, y_n + d).$$

gaSi is ucnobi  $a_n$  koeficientebis gansazRvra, kupraZis Tanaxmad, SeiZl eba moyvanil i j amis wevrebis orTogonal izaciis saSual ebiT sasazRvro pirobebis gamoyenebiT, romel ic garkveul sirTul eebTanaa dakavSirebul i.

moyvanil i gamosaxul ebis Tanaxmad, saZiebel i  $f(x)$  funqcia warmodgenil ia cnobil i grinis funqciebis j amis saxiT. yovel grinis funqciaSi figurirebs regul arizaciis  $d$  parametric, roml is arsebobac uzrunvel yofs maT karg sigl uves da Sesabamisad TviT  $f(x)$  funqciis sigl uves sxeul is  $(\Gamma)$  zedapirze. aqedan gamomdinare moyvanil mwkrivis kargi kreadoba gaaCnia  $(\Gamma)$  zedapiris gaswvriV da amitom ucnobi  $a_n$  koeficientebis sapovnel ad ufro moxerxebul ia kol okaciis meTodis gamoyeneba. amisaTvis CavsvaT aRniSnul i mwkrivis gamosaxul eba sasazRvro pirobaSi. miviRebT:

$$\sum_{n=1}^N a_n \hat{W}G(x, y_n + d) \Big|_{x \in (\Gamma)} = -\hat{W}\varphi(x) \Big|_{x \in (\Gamma)}.$$

Tu moviTxovT am sasazRvro pirobis Sesrul ebas  $(\Gamma)$  zedapiris  $N$  raodenobis sxvadasxva wertil Si (kol okaciis wertil ebSi), maSin ucnobi  $a_n$  koeficientebis mimarT miviRebT wrfiv al gebrul gantol ebaTa sistemas

$$\sum_{n=1}^N a_n \hat{W}G(y_m, y_n + d) = -\hat{W}\varphi(y_m), \quad m=1, 2, \dots, N.$$

am gantol ebaTa sistemas ar gaaCnia singul aroba radgan grinis funqciis argumenti gansxvavdeba nul isgan maSinac ki, rodesac  $m=n$ . misi amoxsna Semdeg kompiuterul i model irebis saSual ebiT xdeba.

difraqciis amocanebSi, rogorc wesi, ganixil eba droSi harmoniul ad cvl adi vel ebi:

$$f(x, t) = f(x) e^{-i\omega t},$$

rodesac drois maxasiaTebel i cnobil ia da aris  $e^{-i\omega t}$ . sawyis operatorul gantol ebas am SemTxvevaSi gaaCnia saxe

$$\Delta f(x) + k^2 f(x) = g(x)$$

da warmoadgens dal amberis tal Rur gantol ebas kompl eqsur formaSi. mas aseve araerTgvarovani hel mhgol cis gantol eba ewodeba. Tu ganixil eba organzomil ebiani amocana, maSin grinis funqciis rol s asrul ebs hankel is funqcia:

$$G(x, y_n) = H_0^{(2)} \left( k \sqrt{(x - x_n)^2 + (y - y_n)^2} \right).$$

bol o ramodenime wl is ganmavl obaSi, Tsu-s gamoyenebiTi el eqtrodinamikis I laboratoriiS mkvl evarTa j gufi muSaobda damxmare gamomxivebl ebis meTodis gaumj obesebaze, raTa SesaZl ebel i yofil iyo aRniSnul i meTodiT aseTi amocanebis amoxsna [33, 34]. sxva meTodebisgan gansxvavebiT, magal iTad momentebis meTodiSgan gansxvavebiT [35], damxmare gamomxivebl ebis meTodis gamoyeneba mkveTrad amcirebs saWiro ucnobebis ricxvs, iZl eva maRal sizustes da swraf kreadobas. Cvens j gufSi ganvITarebul i dgm gaxda mZl avri iaraRi zemoT aRniSnul i probl emebis Sesaswavl ad.

**miRebul i Sedegebis samarTI ianoba.** sadisertacio naSromis fargl ebSi miRebul i ricxviTi eqsperimentebis Sedegebis marTebul oba mowmdeba sxeul is zedapirze sasazRvro pirobebis Sestrul ebiT da aseve maTi fizikuri arsis gaanalizebiT. agreTve, kerZo SemTxvevebSi, anal izurad miRebul SedegebTan SedarebiT.

**sadisertacio naSromis mokl e mimoxil va.** sadisertacio naSromi Sedgeba sami Tavisgan. yovel i Tavi iwyeba amocanis dasmiT da Sesabamisi maTematikuri aparatis Camoyal ibebiT roml is saSual ebiT ixsneba es amocana. Semdeg moyvanilia, Sesabamisi ricxviTi eqsperimentebis Sedegebi, romel nic miRebul ia kompiuterul i model irebis saSual ebiT. yovel amocanisaTvis Seqmnil ia programul i paketi, romel Sic SesaZl oa struqturis yvel a parametris Secvla da mraval i saintereso ricxviTi eqsperimentebis Catareba maRal i sizustiT.

disertaciis pirvel TavSi ganxil eba droSi harmoniul i el eqtromagnituri tal Ris difraqcia, sasrul i zomebis meserze, romel ic moTavsebul ia Tavisufal sivrceSi da Semdeg sasrul i zomebis mqone diel eqtriksi. miRebul ia kirali uri da aseve uaryofiti gardatexis mqone struqturibi. difraqciis amocanasTan erTad ganxil eba antenuri amocana, rodesac dagemul i vel is wyaro struqturis SigniT imyofeba. kerZod, napovnia struqturis parametrebi brtyel i diagramis, kirali uri Tvisebebis da aseve uaryofiti gardatexis misaRebad.

meore TavSi ganxil eba brtyel i, droSi harmoniul i tal Ris difraqcia usasrul o orperiodul meserze. orperiodul s vuwodebT organzomil ebian mesers, romel sac gaaCnia ori periodi urTierTmarTobul i mimarTul ebiT. ganxil eba mesris el ementis formis ramodenime SemTxveva. miRebul ia struqturis parametrebis mniSvnel obebi rodesac igi garkveul sixSireebisaTvis srul iad amrekl zedapirs Seesabameba, an aris srul iad gamWvirval e.

mesame Tavi exeba brtyel i, droSi harmoniul i tal Ris difraqcias sistemaze, romel sac qmnis usasrul o orperiodul i meseri da brtyel i usasrul o diel eqtrikul i fena. ganxil eba ori gansxvavebul i SemTxveva, rodesac meseri imyofeba fenis SigniT da aseve mis maxl obl ad. moyvanilia sami maTematikuri meTodi aseTi saxis amocanebis amosaxsnel ad. moyvanilia aseve zogierTi miRebul i ricxviTi Sedegebi.

## Tavi I

el eqtromagnituri tal Ris difraqcia Tavisufal sivrceSi da  
diel eqtrikSi moTavsebul sasrul i zomebis samganzomil ebian  
periodul meserze

## zogadi mimoxil va

pirvel i Tavi Sedgeba sam paragrafisgan:

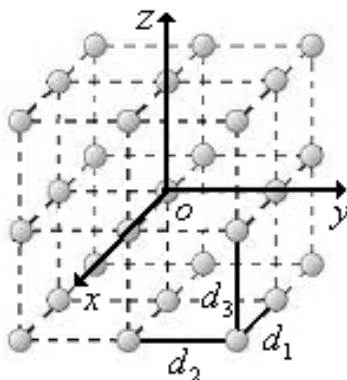
pirvel paragrafsi ganxil eba difraqcia meserze, rodesac is Tavisufal garemoSi imyofeba. mesris el ementebSi aRZrul i denis ganawil eba iZebneba Sesabamis sasazRvro pirobidan.

meore paragrafsi meseri moTavsebul ia sasrul i zomebis diel eqtriksi. diel eqtriki SemosazRvrul ia gl uvi zedapiriT da gaaCnia kompl eqsuri diel eqtrikul i SeRwevadoba. Sesabamisad mas gaaCnia danakargebi. aseTi metal o - diel eqtrikul i struqturis Teoriul i gamokvl eva moITxovs damxmare gamomsxivebl ebis meTodebis gamoyenebas.

mesame paragrafsi moyvanil ia Seqmnil i kodis saSual ebiT miRebul i ricxviti eqsperimentis Sedegebi. ganxil eba mesris oTxi sxvadasxva rezonansul i el ementi. esenia: koncentrirebul i ori gamtari Ria rgol i, gamtari  $\Omega$  el ementi, gamtari spiral i da aseve gamtari kasinis el ementi. gamokvl eul i struqturabis parametrebi mocemul ia dayvanil erTeul ebSi, rac xdis miRebul Sedegebs samarTI ians sixSiris farTo diapazonSi, sadac SeiZl eba gamoyenebul iqnas maqsvel is kl asikuri Teoria.

### \$1.1 el eqtromagnituri tal Ris difraqcia sasrul i zomebis meserze Tavisufal garemoSi

**amocanis dasma.** ganxil oT Tavisufal garemoSi moTavsebul i sasrul i zomebis samganzomil ebiani meseri, romel ic Sedgeba rezonansul i Tvisebebis mqone gamtar el ementebisagan (nax. 1.1.1). mesris periodi sakoordinato RerZebis gaswrviv Sesabamisad avRniSnoT rogorc  $d_1, d_2, d_3$ . moxerxebul ia ganxil ul iqnas kerZo SemTxveva, rodesac yovel i sakoordinato RerZis gaswrviv gagvaCnia el ementebis kenti raodenoba. amitom CavTval oT, rom el ementebis srul i raodenoba meserSi udris  $(2N+1)(2M+1)(2P+1)$ , sadac  $N, M, P$  fiqsirebul i ricxvebia.



nax. 1.1.1 periodul i meseri

mesris el ementi warmoadgens mcire  $dr_0$  radiusis mqone gamtars. unda aRiniSnos, rom Camoyal ibebul i Teoria aris zogadi da amitom araa dakonkretebul i Tu ra forma gaaCnia am el ements. es Teoria SeiZl eba

gamoyenebul iqnas sxvadasxva el ementebis SemTxvevaSi. mesris periodebi unda aRematebodes misi el ementebis zomebs, imisaTvis rom ar hqondes adgil i el ementebis urTierTgadakveTas.

ganxil ul mesers ecema cnobil i, droSi harmoniul ad cvl adi, el eqtromagnituri tal Ra  $\vec{E}_{inc}(\vec{r})$ ,  $\vec{H}_{inc}(\vec{r})$ , sadac  $\vec{r}$  dakvirvebis wertil is radiusveqtoria. drois maxasiaTebel ia  $e^{-i\omega t}$ . dacemul i tal Ra aCens mesris yovel el ementSi denis da muxtis ganawil ebas, rac warmoadgens meoradi (gabneul i vel is) wyaros. Cveni amocanaa vipovoT denis da muxtis es ganawil eba da Sesabamisad difraqciis Sedegad mesridan gabneul i  $\vec{E}_s(\vec{r})$ ,  $\vec{H}_s(\vec{r})$  vel i.

**amocanis amoxsnis meTodi.** mesris central uri el ementis gaswriv ganvixil oT  $\vec{r}_0\{x_0, y_0, z_0\}$  radiusveqtori. maSin sxva el ementis radiusveqtori, roml is nomeria  $n, m, p$ , Caiwereba rogorc  $\vec{r}_{n,m,p}\{x_n, y_m, z_p\}$ , sadac

$$\begin{cases} x_n = x_0 + nd_1, \\ y_m = y_0 + md_2, \\ z_p = z_0 + pd_3, \end{cases} \begin{cases} -N \leq n \leq N, \\ -M \leq m \leq M, \\ -P \leq p \leq P. \end{cases}$$

ucnobi gabneul i vel i unda akmayofil ebdes maqsvel is gantol ebaTa sistemas da sasazRvro pirobas mesris yovel i el ementis zedapiris gaswriv:

$$\vec{E}_{inc}(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0 + \vec{E}_s(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0 = 0, \quad \begin{cases} -N \leq n' \leq N, \\ -M \leq m' \leq M, \\ -P \leq p' \leq P, \end{cases} \quad (1.1.1)$$

sadac  $\vec{\tau}_0$  erTeul ovani tangencial uri veqtoria.

gabneul i vel i  $\vec{r}$  dakvirvebis wertil Si Sedgeba yovel i el ementidan wamosul vel ebisgan:

$$\vec{E}_s(\vec{r}) = \sum_{n,m,p} \vec{E}_{n,m,p}(\vec{r}), \quad \vec{H}_s(\vec{r}) = \sum_{n,m,p} \vec{H}_{n,m,p}(\vec{r}).$$

am vel ebis sapovnel ad moxerxebul ia gamoyenebul iqnas potencial ebis meTodi, roml is Tanaxmad ucnobi gabneul i vel i SegviZl ia warmovidginoT rogorc

$$\vec{E}_s(\vec{r}) = -grad\varphi(\vec{r}) + i\omega\vec{A}(\vec{r}), \quad \vec{H}_s(\vec{r}) = (1/\mu_0)rot\vec{A}(\vec{r}),$$

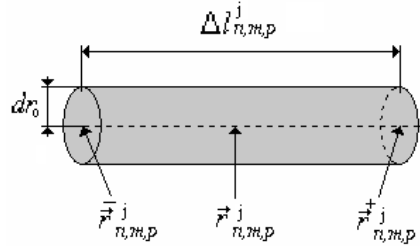
sadac

$$\vec{A}(\vec{r}) = (\mu_0/4\pi) \sum_{n,m,p} \int_{l_{n,m,p}} I_{n,m,p} G(\vec{r}, \vec{r}_{n,m,p}) d\vec{l}, \quad \varphi(\vec{r}) = (1/4\pi\epsilon_0) \sum_{n,m,p} \int_{l_{n,m,p}} \sigma_{n,m,p} G(\vec{r}, \vec{r}_{n,m,p}) dl, \quad (1.1.2)$$

$$G(\vec{r}, \vec{r}_{n,m,p}) = e^{ik_0|\vec{r}-\vec{r}_{n,m,p}|} / |\vec{r}-\vec{r}_{n,m,p}|, \quad k_0 = \omega\sqrt{\mu_0\epsilon_0}, \quad \sigma_{n,m,p} = -(i/\omega)dI_{n,m,p}/dl. \quad (1.1.3)$$

aq  $I_{n,m,p}$  da  $\sigma_{n,m,p}$  mesris  $l_{n,m,p}$  el ementSi aRZrul i ucnobi denis da muxtebis ganawil ebaa.

davyoT mesris yovel i el ementi didi  $K$  raodenobis mcire sigrZis  $\Delta l_{n,m,p}^j$  segmentebad ( $j=1,2,\dots,K$ ). yovel i segmenti davaxasiaToT central uri  $\vec{r}_{n,m,p}^j$  da  $\vec{r}_{n,m,p}^{j+}$ ,  $\vec{r}_{n,m,p}^{j-}$  kidura wertil ebiT (nax. 1.1.2).



nax. 1.1.2 segmentis geometria mesris el ementiSi

segmentebis  $K$  raodenoba aviRoT sakmarisi imisaTvis rom SegveZI os ugul ebel vyoT denis  $I_{n,m,p}$  cvl il eba yovel maTganis gaswvriV. maSasadame CavTval oT, rom yovel  $\Delta l_{n,m,p}^j$  segmentSi gaedineba mudmivi amplitudis  $I_{n,m,p}^j$  deni. es SesaZI oa im SemTxvevaSi, Tu am segmentis bol oebSi imyofeba ori urTierTsapirisiSpiro niSnis muxti  $+q_{n,m,p}^j$  da  $-q_{n,m,p}^j$ , sadac uwyvetobis gantol ebidan gamomdinare

$$q_{n,m,p}^j = -(i/\omega) I_{n,m,p}^j.$$

naTqvamis gaTval iswinebiT potencial ebis gamosaxul ebebSi integrireba mesris el ementiS gaswvriV unda Cavanacvl oT j amiT:

integral istvis, romel ic veqtorul i potencial is gamosaxul ebaSi figurirebs, miviRebT:

$$\int_{l_{n,m,p}} I_{n,m,p} G(\vec{r}, \vec{r}_{n,m,p}) d\vec{l} \approx \sum_j I_{n,m,p}^j G(\vec{r}, \vec{r}_{n,m,p}^j) \Delta l_{n,m,p}^j.$$

skal arul potencial istvis mivaqci oT yuradReba imas rom TiToeul  $\Delta l_{n,m,p}^j$  segmentze imyofeba ori muxti. amis gamo unda davveroT

$$\begin{aligned} \int_{l_{n,m,p}} \sigma_{n,m,p} G(\vec{r}, \vec{r}_{n,m,p}) dl &\approx -(i/\omega) \sum_j I_{n,m,p}^j \left[ G\left(\vec{r}, \vec{r}_{n,m,p}^{j+}\right) - G\left(\vec{r}, \vec{r}_{n,m,p}^{j-}\right) \right] = \\ &= -(i/\omega) \sum_j I_{n,m,p}^j \Delta G(\vec{r}, \vec{r}_{n,m,p}^j). \end{aligned}$$

unda aRiniSnos, rom sasrul i sxvaoba  $\Delta G(\vec{r}, \vec{r}_{n,m,p}^j)$  bol o gamosaxul ebaSi ar icvl eba diferencial iT, radgan aseTi Canacvl eba gaxdeba samarTliani el ementarul i segmentebis ufro did raodenobasatvis, rac model irebisas moiTxovs kompiuteris gacil ebiT ufro met resursebs.

Tu SevitanT integral ebis miRebul mniSvnel obebs potencial ebis (1.1.2) gamosaxul ebebSi, maSin gveqneba:

$$\vec{A}(\vec{r}) = (\mu_0/4\pi) \sum_{n,m,p} \sum_j I_{n,m,p}^j G(\vec{r}, \vec{r}_{n,m,p}^j) \Delta l_{n,m,p}^j, \quad \varphi(\vec{r}) = -(i/4\pi\omega\epsilon_0) \sum_{n,m,p} \sum_j I_{n,m,p}^j \Delta G(\vec{r}, \vec{r}_{n,m,p}^j),$$

$$\Delta G(\vec{r}, \vec{r}_{n,m,p}^j) = G\left(\vec{r}, \vec{r}_{n,m,p}^{j+}\right) - G\left(\vec{r}, \vec{r}_{n,m,p}^{j-}\right).$$

**gabneul i vel is gamosaxul eba.** veqtorul i da skal arul i potencial ebis meSveobiT SegviZl ia gamovsaxoT ucnobi gabneul i vel i:

$$\vec{E}_s(\vec{r}) = -grad\varphi(\vec{r}) + i\omega\vec{A}(\vec{r}), \quad \vec{H}_s(\vec{r}) = (1/\mu_0) rot\vec{A}(\vec{r}).$$

Tu Semovi tanT aRni Svnas

$$\tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) = e^{ik_0|\vec{r}-\vec{r}_{n,m,p}^j|} \left( ik_0|\vec{r}-\vec{r}_{n,m,p}^j| - 1 \right) / |\vec{r}-\vec{r}_{n,m,p}^j|^3, \quad (1.1.4)$$

maSin garkveul i gamoTvl ebis Sedegad mi vi RebT

$$rot\vec{A}(\vec{r}) = (\mu_0/4\pi) \sum_{n,m,p} \sum_j I_{n,m,p}^j \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \times \Delta\vec{L}_{n,m,p}^j,$$

$$grad\varphi(\vec{r}) = -(i/4\pi\omega\epsilon_0) \sum_{n,m,p} \sum_j I_{n,m,p}^j \Delta \left[ \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \right],$$

sadac

$$\Delta \left[ \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \right] = \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^{j+}) (\vec{r} - \vec{r}_{n,m,p}^{j+}) - \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^{j-}) (\vec{r} - \vec{r}_{n,m,p}^{j-}).$$

gabneul i vel i Semdegnai rad gamoi saxeba:

$$\vec{E}_s(\vec{r}) = (i/4\pi\omega\epsilon_0) \sum_{n,m,p} \sum_j I_{n,m,p}^j \left\{ k_0^2 G(\vec{r}, \vec{r}_{n,m,p}^j) \Delta\vec{L}_{n,m,p}^j + \Delta \left[ \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \right] \right\}, \quad (1.1.5)$$

$$\vec{H}_s(\vec{r}) = (1/4\pi) \sum_{n,m,p} \sum_j I_{n,m,p}^j \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \times \Delta\vec{L}_{n,m,p}^j. \quad (1.1.6)$$

**denis ganawil ebis gansazRvra mesris el ementebSi.** denebis ucnobi  $I_{n,m,p}^j$  ampl itudebs vipoviT sasazRvro pirobidan, romel sac gabneul i vel i unda akmayofil ebdes yovel  $\Delta\vec{L}_{n',m',p'}^k$  segmentis gaswvri v. sasazRvro pirobidan gamomdinare

$$\vec{E}_s(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{L}_{n',m',p'}^k = -\vec{E}_{inc}(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{L}_{n',m',p'}^k.$$

Tu movaxdenT vel is gamosaxul ebis Casmas am pirobaSi, maSin ucnobi ampl itudebis mimarT mi vi RebT wrfiv al gebrul gantol ebaTa sistemas:

$$\sum_{n,m,p} \sum_j Z_{n,m,p,n',m',p'}^{j,k} I_{n,m,p}^j = \vec{E}_{inc}(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{L}_{n',m',p'}^k, \quad (1.1.7)$$

$$\begin{cases} -N \leq n' \leq N, \\ -M \leq m' \leq M, \\ -P \leq p' \leq P, \end{cases} \quad k = 1, 2, \dots,$$

sadac

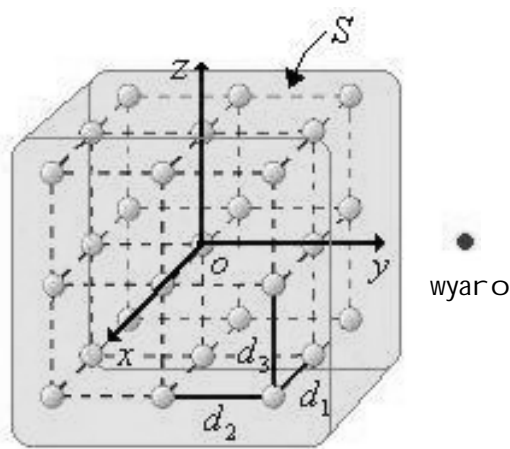
$$Z_{n,m,p,n',m',p'}^{j,k} = -(i/4\pi\omega\epsilon_0) \times \left\{ k_0^2 G(\vec{r}_{n',m',p'}^k + d\vec{r}_0, \vec{r}_{n,m,p}^j) \Delta\vec{L}_{n,m,p}^j + \Delta \left[ \tilde{G}(\vec{r}_{n',m',p'}^k + d\vec{r}_0, \vec{r}_{n,m,p}^j) (\vec{r}_{n',m',p'}^k - \vec{r}_{n,m,p}^j + d\vec{r}_0) \right] \right\} \cdot \Delta\vec{L}_{n',m',p'}^k. \quad (1.1.8)$$

gantol ebebis raodenoba sistemaSi tol ia  $K(2N+1)(2M+1)(2P+1)$ , rac udris ucnobi ampl itudebis raodenobas. am sistemis amoxsna kompiuteris saSual eb iT xdeba, ris Semdegadac ucnobi gabneul i vel i (1.1.5) da (1.1.6) formul ebis saxiT Cai wereba.



## \$1.2 difraqcia diel eqtrikSi moTavsebul periodul meserze

**amocanis dasma.** davuSvaT rom, zemoT ganxil ul i meseri moTavsebul ia sasrul i zomebis  $\varepsilon = \varepsilon' + i\varepsilon''$  kompl eqsuri diel eqtrikul i da  $\mu$  magnituri SeRwevadobebis mqone diel eqtrikSi (nax. 1.2.1). diel eqtriki SemosazRvrul ia gl uvi  $S$  zedapiriT. sivrcis garkveul wertil Si imyofeba wertil ovani, cnobil i el eqtromagnituri  $\vec{E}_{inc}(\vec{r})$ ,  $\vec{H}_{inc}(\vec{r})$  tal Ris wyaro. amocanaa vipovoT difraqciis Sedegad miRebul i vel i struqturis SigniT da gareT. Cven unda ganvixil oT ori gansxvavebul i SemTxveva, rodesac dacemul i vel is wyaro imyofeba struqturis gareT da mis SigniT. pirvel SemTxvevaSi, Tu igi Sor manZil ze imyofeba struqturidan, maSin gveqneba brtyel i dacemul i  $\vec{E}_{inc}(\vec{r})$ ,  $\vec{H}_{inc}(\vec{r})$  tal Ra.



nax. 1.2.1 diel eqtrikSi Casmul i periodul i meseri

Tu dacemul i vel is wyaro struqturis gareT imyofeba, maSin gare srul i  $\vec{E}_{out}(\vec{r})$ ,  $\vec{H}_{out}(\vec{r})$  vel i Sedgeba dacemul i  $\vec{E}_{inc}(\vec{r})$ ,  $\vec{H}_{inc}(\vec{r})$  da diel eqtrikis  $S$  zedapiridan gabneul i ucnobi  $\vec{E}_1(\vec{r})$ ,  $\vec{H}_1(\vec{r})$  vel ebisagan:

$$\vec{E}_{out}(\vec{r}) = \vec{E}_1(\vec{r}) + \vec{E}_{inc}(\vec{r}), \quad \vec{H}_{out}(\vec{r}) = \vec{H}_1(\vec{r}) + \vec{H}_{inc}(\vec{r}).$$

struqturis SigniT srul i  $\vec{E}_{in}(\vec{r})$ ,  $\vec{H}_{in}(\vec{r})$  vel i Sedgeba mesris mier gabneul  $\vec{E}_s(\vec{r})$ ,  $\vec{H}_s(\vec{r})$  da diel eqtrikis  $S$  zedapiridan SigniT gabneul ucnob  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel ebisagan:

$$\vec{E}_{in}(\vec{r}) = \vec{E}_2(\vec{r}) + \vec{E}_s(\vec{r}), \quad \vec{H}_{in}(\vec{r}) = \vec{H}_2(\vec{r}) + \vec{H}_s(\vec{r}).$$

im SemTxvevaSi, rodesac dacemul i vel is wyaro struqturis SigniT imyofeba, srul i gare vel i warmoadgens mxol od im ucnob  $\vec{E}_1(\vec{r})$ ,  $\vec{H}_1(\vec{r})$  vel s, romel sac diel eqtrikis  $S$  zedapiri asxivebs:

$$\vec{E}_{out}(\vec{r}) = \vec{E}_1(\vec{r}), \quad \vec{H}_{out}(\vec{r}) = \vec{H}_1(\vec{r}).$$

srul i Sida vel i am SemTxvevaSi Sedgeba dacemul i  $\vec{E}_{inc}(\vec{r})$ ,  $\vec{H}_{inc}(\vec{r})$ , mesridan gabneul i  $\vec{E}_s(\vec{r})$ ,  $\vec{H}_s(\vec{r})$  da  $S$  zedapiridan SigniT gadasxivebul i  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel ebisagan:

$$\vec{E}_{in}(\vec{r}) = \vec{E}_2(\vec{r}) + \vec{E}_s(\vec{r}) + \vec{E}_{inc}(\vec{r}), \quad \vec{H}_{in}(\vec{r}) = \vec{H}_2(\vec{r}) + \vec{H}_s(\vec{r}) + \vec{H}_{inc}(\vec{r}).$$

srul i Sida da gare vel ebi unda akmayofil ebdnen sasazRvro pirobebs diel eqtrikis  $S$  zedapirze da aseve mesris yovel i el enmentis gaswrviv.

dien eqtrikis  $S$  zedapirze moitxoveba srul i vel is tangencial uri mdgenel is uwyvetobis piroba. Cven ganvixil avT difraqciis amocanas samganzomil ebian strukturaze da maSasadame, sasazRvro piroba unda srul debodes  $S$  zedapiris nebismieri tangencial is gaswrviv. avagoT am zedapiris yovel wertil Si ori urTierTmarTobul i erTeul ovani mxebi veqtori  $\vec{\tau}_1$  da  $\vec{\tau}_2$ . gasagebia rom Tu sasazRvro piroba srul deba orive veqtoris gaswrviv maSin is nebismieri sxva tangencial is gaswrviv Sesrul deba. naTqvamis Tanaxmad

$$\begin{cases} \vec{E}_{in}(\vec{r}_S) \cdot \tau_1 = \vec{E}_{out}(\vec{r}_S) \cdot \tau_1, \\ \vec{H}_{in}(\vec{r}_S) \cdot \tau_1 = \vec{H}_{out}(\vec{r}_S) \cdot \tau_1, \\ \vec{E}_{in}(\vec{r}_S) \cdot \tau_2 = \vec{E}_{out}(\vec{r}_S) \cdot \tau_2, \\ \vec{H}_{in}(\vec{r}_S) \cdot \tau_2 = \vec{H}_{out}(\vec{r}_S) \cdot \tau_2, \end{cases} \quad (1.2.1)$$

sadac  $\vec{r}_S$  diel eqtrikis  $S$  zedapiris wertil is radiusveqtoria.

mesris el ementebisaTvis moitxoveba srul i Sida vel is tangencial uri mdgenel is nul Tan tol obis piroba:

$$\vec{E}_{in}(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0 = 0. \quad (1.2.2)$$

pirvel SemTxvevaSi, rodesac dacemul i vel is wyaro gareT imyofeba, (1.2.1) da (1.2.2) sasazRvro pirobebi dan mi vi RebT:

$$\begin{cases} \vec{E}_2(\vec{r}_S) \cdot \tau_1 - \vec{E}_1(\vec{r}_S) \cdot \tau_1 + \vec{E}_s(\vec{r}_S) \cdot \tau_1 = \vec{E}_{inc}(\vec{r}_S) \cdot \tau_1, \\ \vec{H}_2(\vec{r}_S) \cdot \tau_1 - \vec{H}_1(\vec{r}_S) \cdot \tau_1 + \vec{H}_s(\vec{r}_S) \cdot \tau_1 = \vec{H}_{inc}(\vec{r}_S) \cdot \tau_1, \\ \vec{E}_2(\vec{r}_S) \cdot \tau_2 - \vec{E}_1(\vec{r}_S) \cdot \tau_2 + \vec{E}_s(\vec{r}_S) \cdot \tau_2 = \vec{E}_{inc}(\vec{r}_S) \cdot \tau_2, \\ \vec{H}_2(\vec{r}_S) \cdot \tau_2 - \vec{H}_1(\vec{r}_S) \cdot \tau_2 + \vec{H}_s(\vec{r}_S) \cdot \tau_2 = \vec{H}_{inc}(\vec{r}_S) \cdot \tau_2, \\ \vec{E}_s(\vec{r}_{n',m',p'} + d\vec{r}) \cdot \vec{\tau}_0 + \vec{E}_2(\vec{r}_{n',m',p'} + d\vec{r}) \cdot \vec{\tau}_0 = 0. \end{cases}$$

meore SemTxvevaSi, anal ogi urad gveqneba

$$\begin{cases} \vec{E}_2(\vec{r}_S) \cdot \tau_1 - \vec{E}_1(\vec{r}_S) \cdot \tau_1 + \vec{E}_s(\vec{r}_S) \cdot \tau_1 = -\vec{E}_{inc}(\vec{r}_S) \cdot \tau_1, \\ \vec{H}_2(\vec{r}_S) \cdot \tau_1 - \vec{H}_1(\vec{r}_S) \cdot \tau_1 + \vec{H}_s(\vec{r}_S) \cdot \tau_1 = -\vec{H}_{inc}(\vec{r}_S) \cdot \tau_1, \\ \vec{E}_2(\vec{r}_S) \cdot \tau_2 - \vec{E}_1(\vec{r}_S) \cdot \tau_2 + \vec{E}_s(\vec{r}_S) \cdot \tau_2 = -\vec{E}_{inc}(\vec{r}_S) \cdot \tau_2, \\ \vec{H}_2(\vec{r}_S) \cdot \tau_2 - \vec{H}_1(\vec{r}_S) \cdot \tau_2 + \vec{H}_s(\vec{r}_S) \cdot \tau_2 = -\vec{H}_{inc}(\vec{r}_S) \cdot \tau_2, \end{cases}$$

$$\vec{E}_s(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0 + \vec{E}_2(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0 = -\vec{E}_{inc}(\vec{r}_{n',m',p'} + d\vec{r}_0) \cdot \vec{\tau}_0.$$

dasmul i amocanis Tanaxmad, unda vipovoT difraqciis Sedegad miRebul i vel ebi diel eqtrikis SigniT da gareT da aseve unda davakmayofil oT (1.2.1), (1.2.2) sasazRvro pirobebi.

**amocanis amoxsnis meTodi.** wina paragrafSi iqna napovni mesris mier gabneul i ucnobi  $\vec{E}_s(\vec{r})$ ,  $\vec{H}_s(\vec{r})$  vel i. misi damokidebul eba ucnobi denis  $I_{n,m,p}^j$  ampl itudebisagan Semdegi formul ebiT gamoisaxebe:

$$\vec{E}_s(\vec{r}) = (i/4\pi\omega\varepsilon_0\varepsilon) \sum_{n,m,p} \sum_j I_{n,m,p}^j \left\{ k^2 G(\vec{r}, \vec{r}_{n,m,p}^j) \Delta_{n,m,p}^j + \Delta \left[ \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \right] \right\}, \quad (1.2.3)$$

$$\vec{H}_s(\vec{r}) = (1/4\pi) \sum_{n,m,p} \sum_j I_{n,m,p}^j \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \times \Delta_{n,m,p}^j, \quad (1.2.4)$$

sadac

$$k = \omega \sqrt{\varepsilon_0 \varepsilon \mu_0 \mu}, \quad G(\vec{r}, \vec{r}_{n,m,p}^j) = e^{ik|\vec{r} - \vec{r}_{n,m,p}^j|} / |\vec{r} - \vec{r}_{n,m,p}^j|,$$

$$\tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) = e^{ik|\vec{r} - \vec{r}_{n,m,p}^j|} (ik|\vec{r} - \vec{r}_{n,m,p}^j| - 1) / |\vec{r} - \vec{r}_{n,m,p}^j|^3,$$

$$\Delta \left[ \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^j) (\vec{r} - \vec{r}_{n,m,p}^j) \right] = \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^{j+}) (\vec{r} - \vec{r}_{n,m,p}^{j+}) - \tilde{G}(\vec{r}, \vec{r}_{n,m,p}^{j-}) (\vec{r} - \vec{r}_{n,m,p}^{j-}).$$

ucnobi  $\vec{E}_1(\vec{r})$ ,  $\vec{H}_1(\vec{r})$  da  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel ebi sapovnel ad gamoviyenoT damxmare gamomsxivebl ebi meTodi. amisaTvis diel eqtrikis zedapiris orive mxridan, Tanabari daSorebiT avagoT ori gl uvi damxmare zedapiri  $S_{in}$ ,  $S_{out}$  da ganval agoT yovel maTganze damxmare wyaroebi. damxmare wyaroebis raodenoba yovel aseT zedapirze unda udrides wertil ebi im raodenobas diel eqtrikis  $S$  zedapirze, sadac Sesabamisi (1.2.1) sasazRvro pirobis Sesrul eba moiTxoveba.

damxmare wyarod moxerxebul ia arCeul i iqnas ori urTierTmarTobul i kombinirebul i dipol i. maTi saSual ebiT SeiZl eba warmodgenil i iqnas nebismieri saxis da nebismieri pol arizaciis mqone vel i. am dipol ebi pol arizaciis veqtorebi, damxmare zedapiris yovel wertil Si miwmarToT  $\vec{\tau}_1$  da  $\vec{\tau}_2$  tangencial ebi paral el urad. Sida wyarobis meSveobiT aRiwereba gare ucnobi  $\vec{E}_1(\vec{r})$ ,  $\vec{H}_1(\vec{r})$  vel i. gare damxmare wyaroebi ki aRwren diel eqtrikis SigniT ucnob  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel s.

damxmare wyaros mier gamomsxivebul i vel istvis moxerxebul ia SemoviRoT aRniSvna  $\vec{E}_{in,out}^{\alpha,\beta}(\vec{r})$ . aq gvaqvs zeda da qveda indeqsebi. zeda indeqsebi gviCvenebs damxmare wyaros nomers ( $\alpha, \beta = 1, 2, \dots$ ). pirvel i an meore qveda indeqsis mixedviT gavigebT romel damxmare zedapiris ekuTvnis es dipol i, frCxil ebSi mdebare indeqsi gviCvenebs dipol is orientacias.

yovel kombinirebul dipol es, damxmare gamomsxivebel Si gaaCnia Tavisi ucnobi ampl ituda. amitom, Tu ganvixil avT ( $\alpha, \beta$ ) damxmare wyaros Sida  $S_{in}$  zedapirze, maSin misi vel i iqneba

$$A_{\alpha,\beta} \vec{E}_{in(\tau_1)}^{\alpha,\beta}(\vec{r}) + B_{\alpha,\beta} \vec{E}_{in(\tau_2)}^{\alpha,\beta}(\vec{r}), \quad A_{\alpha,\beta} \vec{H}_{in(\tau_1)}^{\alpha,\beta}(\vec{r}) + B_{\alpha,\beta} \vec{H}_{in(\tau_2)}^{\alpha,\beta}(\vec{r}).$$

anal ogiurad, gare  $S_{out}$  zedapiris ( $\gamma, \delta$ ) wyarosTvis gveqneba

$$C_{\gamma,\delta} \vec{E}_{out(\tau_1)}^{\gamma,\delta}(\vec{r}) + D_{\gamma,\delta} \vec{E}_{out(\tau_2)}^{\gamma,\delta}(\vec{r}), \quad C_{\gamma,\delta} \vec{H}_{out(\tau_1)}^{\gamma,\delta}(\vec{r}) + D_{\gamma,\delta} \vec{H}_{out(\tau_2)}^{\gamma,\delta}(\vec{r}).$$

aq  $A_{\alpha,\beta}$ ,  $B_{\alpha,\beta}$ ,  $C_{\gamma,\delta}$ ,  $D_{\gamma,\delta}$  damxmare wyaroebis ucnobi ampl itudebia.

kombini rebul i dipol is mier gamosxivebul i vel is zogadi gamosaxul eba cnobil ia Teoriidan [36]:

$$\vec{E}(\vec{R}) = \vec{E}_{el}(\vec{R}) + \sqrt{\mu_0 \mu / \varepsilon_0 \varepsilon} \vec{E}_{mag}(\vec{R}), \quad \vec{H}(\vec{R}) = \vec{H}_{el}(\vec{R}) + \sqrt{\mu_0 \mu / \varepsilon_0 \varepsilon} \vec{H}_{mag}(\vec{R}),$$

sadac

$$\vec{E}_{el}(\vec{R}) = (e^{ikR} / 4\pi \varepsilon_0 \varepsilon) \left\{ (1/R^3 - ik/R^2) \left[ 3\vec{R}_0 \cdot (\vec{R}_0 \cdot \vec{\tau}_{el}) - \vec{\tau}_{el} \right] - (k^2/R) (\vec{R}_0 \times (\vec{R}_0 \times \vec{\tau}_{el})) \right\},$$

$$\vec{H}_{el}(\vec{R}) = -(i\omega e^{ikR} / 4\pi) (1/R^2 - ik/R) (\vec{\tau}_{el} \times \vec{R}_0);$$

$$\vec{E}_{mag}(\vec{R}) = (k^2 e^{ikR} / 4\pi) (1/R^2 - ik/R) (\vec{\tau}_{mag} \times \vec{R}_0);$$

$$\vec{H}_{mag}(\vec{R}) = (e^{ikR} / 4\pi) \left\{ (1/R^3 - ik/R^2) \left[ 3\vec{R}_0 \cdot (\vec{R}_0 \cdot \vec{\tau}_{mag}) - \vec{\tau}_{mag} \right] - (k^2/R) (\vec{R}_0 \times (\vec{R}_0 \times \vec{\tau}_{mag})) \right\}.$$

aq  $\vec{R}_0$  erTeul ovani veqtoria, romelic aris mimarTuli dipolidan dakvirvebis wertil Si,  $R$  warmoadgens manZil s dipol sa da dakvirvebis wertil s Soris, xolo  $\vec{\tau}$  dipol is pol arizaciis erTeul ovani veqtoria

ucnobi  $\vec{E}_1(\vec{r})$ ,  $\vec{H}_1(\vec{r})$  da  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel ebisTvis gveqneba:

$$\vec{E}_1(\vec{r}) = \sum_{\alpha, \beta} \left[ A_{\alpha, \beta} \vec{E}_{in(\tau_1)}^{\alpha, \beta}(\vec{r}) + B_{\alpha, \beta} \vec{E}_{in(\tau_2)}^{\alpha, \beta}(\vec{r}) \right], \quad (1.2.5)$$

$$\vec{H}_1(\vec{r}) = \sum_{\alpha, \beta} \left[ A_{\alpha, \beta} \vec{H}_{in(\tau_1)}^{\alpha, \beta}(\vec{r}) + B_{\alpha, \beta} \vec{H}_{in(\tau_2)}^{\alpha, \beta}(\vec{r}) \right], \quad (1.2.6)$$

$$\vec{E}_2(\vec{r}) = \sum_{\gamma, \delta} \left[ C_{\gamma, \delta} \vec{E}_{out(\tau_1)}^{\gamma, \delta}(\vec{r}) + D_{\gamma, \delta} \vec{E}_{out(\tau_2)}^{\gamma, \delta}(\vec{r}) \right], \quad (1.2.7)$$

$$\vec{H}_2(\vec{r}) = \sum_{\gamma, \delta} \left[ C_{\gamma, \delta} \vec{H}_{out(\tau_1)}^{\gamma, \delta}(\vec{r}) + D_{\gamma, \delta} \vec{H}_{out(\tau_2)}^{\gamma, \delta}(\vec{r}) \right]. \quad (1.2.8)$$

maSasadame amocana dayvanilia damxmare wyaroebis ucnobi  $A_{\alpha, \beta}$ ,  $B_{\alpha, \beta}$ ,  $C_{\gamma, \delta}$ ,  $D_{\gamma, \delta}$  amplitudebis da mesris el ementebSi aRZruli denis  $I_{n, m, p}^j$  amplitudebis gansazRvraze.

**ucnobi amplitudebis gansazRvra.**  $A_{\alpha, \beta}$ ,  $B_{\alpha, \beta}$ ,  $C_{\gamma, \delta}$ ,  $D_{\gamma, \delta}$  da  $I_{n, m, p}^j$  ucnob amplitudebs gavnsazRvraVT (1.2.1) da (1.2.2) sasazRvro pirobebidan. Tu am sasazRvro pirobebsi CavsvavT vel ebis (1.2.5) - (1.2.8) gamosaxul ebebs, maSin miviRebT ucnobi amplitudebis mimarT wrfiv algebrul gantol ebaTa sistemas. im SemTxvevaSi, rodesac dacemuli vel is wyaro struqturis gareT imyofeba, aRniSnul sistemas eqneba saxe

$$\begin{cases} \vec{E}_2(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 - \vec{E}_1(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 + \vec{E}_s(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 = \vec{E}_{inc}(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1, \\ \vec{H}_2(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 - \vec{H}_1(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 + \vec{H}_s(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1 = \vec{H}_{inc}(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_1, \\ \vec{E}_2(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 - \vec{E}_1(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 + \vec{E}_s(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 = \vec{E}_{inc}(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2, \\ \vec{H}_2(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 - \vec{H}_1(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 + \vec{H}_s(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2 = \vec{H}_{inc}(\vec{r}_{\eta, \vartheta}) \cdot \vec{\tau}_2, \\ \vec{E}_s(\vec{r}_{n', m', p'}^k + d\vec{r}_0) \cdot \Delta \vec{l}_{n', m', p'}^k + \vec{E}_2(\vec{r}_{n', m', p'}^k + d\vec{r}_0) \cdot \Delta \vec{l}_{n', m', p'}^k = 0, \end{cases}$$

sadac  $\eta, \vartheta$  diel eqtrikis  $S$  zedapiris wertil is nomeria, romel sic sasazRvro piroba iwereba ( $\eta, \vartheta = 1, 2, \dots$ ),  $k = 1, 2, \dots$

im SemTxvevaSi, rodesac wyaro imyofeba struqturis SigniT, anal ogi urad mi vi RebT

$$\begin{cases} \vec{E}_2(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 - \vec{E}_1(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 + \vec{E}_s(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 = -\vec{E}_{inc}(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1, \\ \vec{H}_2(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 - \vec{H}_1(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 + \vec{H}_s(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1 = -\vec{H}_{inc}(\vec{r}_{\eta,9}) \cdot \vec{\tau}_1, \\ \vec{E}_2(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 - \vec{E}_1(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 + \vec{E}_s(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 = -\vec{E}_{inc}(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2, \\ \vec{H}_2(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 - \vec{H}_1(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 + \vec{H}_s(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2 = -\vec{H}_{inc}(\vec{r}_{\eta,9}) \cdot \vec{\tau}_2, \\ \vec{E}_s(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{l}_{n',m',p'}^k + \vec{E}_2(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{l}_{n',m',p'}^k = -\vec{E}_{inc}(\vec{r}_{n',m',p'}^k + d\vec{r}_0) \cdot \Delta\vec{l}_{n',m',p'}^k. \end{cases}$$

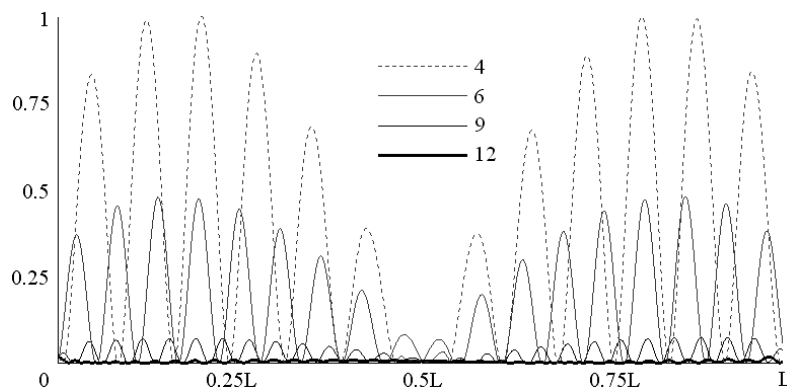
am sistemebis amoxsna kompiuteris saSual ebiT xdeba, ris Sedegad vpoul obT damxmare wyaroebis amplitudebs da aseve denis amplitudebs mesris el ementebis gaswvri. amis Semdeg vpoul obT ucnob gare da Sida vel ebs.

### \$1.3 ricxviTi eqsperimentis Sedegebi

ricxviT eqsperimentebande, pirvel rigSi, Semowmda Sesabamisi al goriTmis sizuste da miRebul i amonaxsnebis kreadoba.

**kreadobis da amoxsnis sizustis Semowmeba.** damxmare gamomsxivebl ebis meTodis gamoyenebisas mniSvel ovania damxmare parametrebis optimal uri SerCeva. damxmare parametrebs warmoadgenen: segmentis sigrZe mesris el ementSi da el ementis radiusi dacemul i tal Ris  $\lambda$  sigrZesTan SedarebiT, damxmare zedapiris daSoreba sxeul is real ur zedapiridan, aseve kol okaciis wertil ebis raodenoba  $\lambda^2$  farTobze. am damxmare parametrebis mniSvel obebzea damokidebul i miRebul i amonaxsnis kreadoba da sizuste. maTi optimal uri mniSvel obebis codna xel s uwyobs rTul i struqturabis el eqtromagnituri Tvisebebis saTanado gamokvl evas ricxviTi eqsperimentebis saSual ebiT.

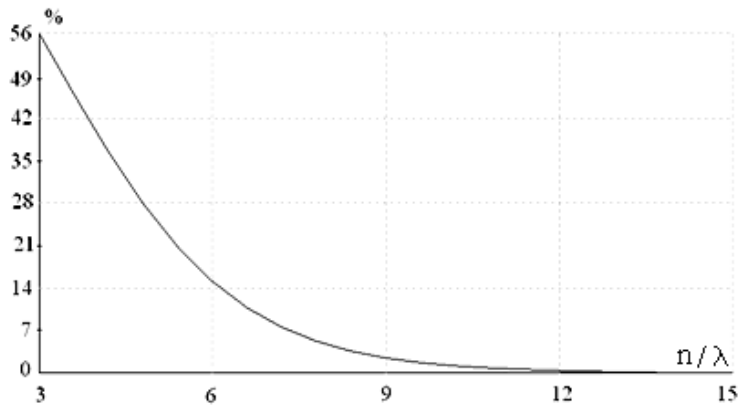
qvemoT moyvanil i naxazi (nax. 1.3.1) gviCvenebs, Tu rogoraa damokidebul i sasazRvro pirobebis Sesrul eba mesris el ementis gaswvri kol okaciis wertil ebis raodenobaze. gadaxris yvel a mniSvel oba danormirebul ia maqsimal ur mniSvel obaze, romelic miReba oTxi kol okaciis wertil is SemTxvevaSi tal Ris sigrZeze.



nax. 1.3.1 cdomil ebis damokidebul eba kol okaciis wertil ebis raodenobaze

rogorc am naxazidan Cans, gadaxra sasazRvro pirobis Sestrul ebidan kol okaciis wertil ebs Soris mcirdeba maTi raodenobis gazrdisas. optimal uri damxmare parametrebis Ziebam gviCvena, rom saukeTeso miaxl oveba el eqtrul ad wvrii mavTul Tan miirweva, rodesac misi  $dr_0$  radiusi imyofeba  $0.03\lambda$  mniSvnel obis fargl ebSi.

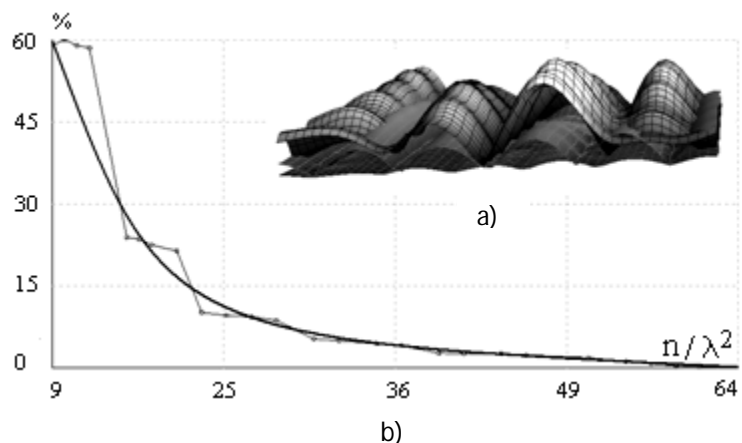
Semdegi naxazi (nax. 1.3.2) gviCvenebs amonaxsnis maqsimal uri cdomil ebis damokidebul ebas  $n/\lambda$  sidideze, romel ic warmoadgens kol okaciis wertil ebis raodenobas tal Ris sigrZeze.



nax. 1.3.2 cdomil ebis damokidebul eba  $n/\lambda$  si di deze

iTvl eba, rom cdomil eba romel ic Seesabameba romel ime konkretul  $n/\lambda$  mniSvnel obas, aris Tanabari mTel i el ementis (mavTul is) gaswvri. es imas niSnavs, rom real uri cdomil eba am mniSvnel obaze ufro nakl ebia. magal iTad, cxra kol okaciis wertil is SemTxvevaSi cdomil eba or procentze nakl ebs Seadgens.

naxazebi 1.3.3 a) da b) gviCvenebs sasazRvro pirobebis Sestrul ebis sizustes  $\vec{E}$  veqtorisaTvis diel eqtrikis zedapirze, kol okaciis wertil ebis sxvadasxva raodenobaze.



nax. 1.3.3 cdomil ebis damokidebul eba kol okaciis wertil ebis raodenobaze diel eqtrikis zedapiris gaswvri

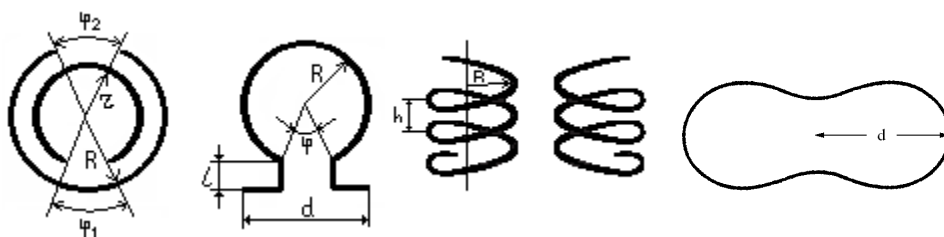
gamoTvl is mrude texilia (b)), radgan rTulia mivaRwioT mis sigl uves. 25 kol okaciis wertil i  $\lambda^2$  farTobze gvaZl evs 10% cdomil ebas. 36 wertil is SemTxvevaSi cdomil eba 3% Seadgens. aseve, cdomil eba

Seadgens mxol od 1%, rodesac gagvaCnia 64 kol okaciis wertil i, rac Seesabameba rva wertil s tal Ris sigrZeze. diel eqtrikis wiboebi da wveroebi Canacvl ebul ia cil indrul i da sferul i zedapirebiT da maTi (momrgval ebis) radiusia  $r_0 \approx 0.03\lambda$ . amave dros, momrgval ebis radiusis es mniSvnel oba gansazRvravs damxmare zedapiris maqsimal ur daSorebas diel eqtrikis real ur zedapiridan. diel eqtrikis zedapiri ar Seicavs Cazneqil nawil ebs da amitom gare damxmare zedapiri SeiZl eba iqnas misgan daSorebul i tal Ris sigrZis rigis manZil ze. Sida damxmare zedapiris aRebul i daSoreba udris momrgval ebis radiuss. rac Seexeba damxmare gamomsxivebl ebs, isini warmoadgenen hiugensis wyaroebis da maTi gamosxiveba mimarTul ia aRsaweri vel isaken.

Semdeg moyvanil ia ricxviTi Sedegebi, romel nic miRebul ia zemoaRniSnul i cdomil ebebis gaTval iswinebiT. es cdomil eba saSual od 2-5% fargl ebSia. rezonansul i sixSireebis SemTxvevaSi cdomil eba matul obs, magram is ar aRemateba 10%. cnobilia, rom praqtikaSi, nebismieri fizikuri sididis gazomva garkveul i sizustiT xdeba. amitom miRebul i ricxviTi Sedegebi Seesabamebian odnav wanacvl ebul parametebis mqone structurebs.

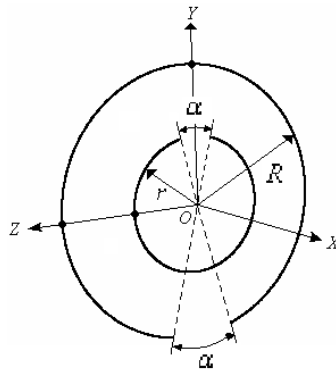
yvel a moyvanil i ricxviTi Sedegi rCeba samarTl iani farTo sixSirul areSi, roml is fargl ebSic SeiZl eba gamoyenebul iqnas maqsvel is gantol ebaTa sistema. amitom, gamokvl eul i structurebis geometriul i parametrebi moyvanil ia dayvanil , tal Ris sigrZis erTeul ebSi.

ganixil eba rezonansul i el ementis oTxi gansxvavebul i forma: ori koncentrirebul i Ria rgol i, berZnul i aso  $\Omega$  formis el ementi, kiral uri el ementi (spiral i) da aseve el ementi, romel sac gaaCnia kasinis mrudis forma (nax. 1.3.4). yovel i el ementi SeiZl eba warmodgenil iqnas, rogorc maRal i vargisianobis mqone rxeviTi konturi, romel sac gaaCnia sakuTari induqtioba, tevadoba da winaRoba.



nax. 1.3.4 mesris el ementis magal iTebi

**ori koncentrirebul i Ria rgol is el eqtrodinamikuri Tvisebebis gamokvl eva.** aq gamokvl eul ia im erTerTi SesaZl o el ementis rezonansul i Tvisebebi, romel ic SeiZl eba iqnas gamoyenebul i kompl eqsuri masal is misaRebad. kerZod, iseTi masal is, romel sac uaryofiTi gardatexis maCvenebl i gaaCnia.

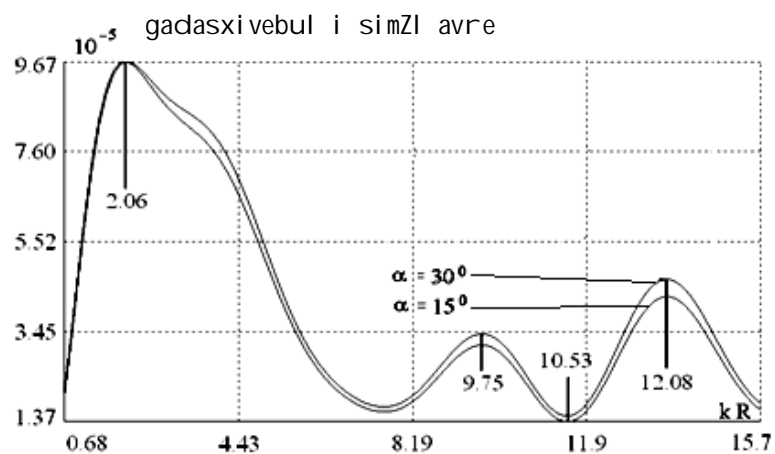


nax.F1.3.5 rezonansul i el ementis geometria

es rezonansul i el ementi warmoadgens  $R$  da  $r=0.5R$  radiusebis mqone koncentrirebul or Ria rgol s [37]. orive rgol is Ria seqtori  $\alpha$  kuTxes Seadgens da am seqtores urTierTsawinaaRmdego orientacia gaaCniaT (nax. 1.3.5).

ganxil ul el ements ecema brtyel i erTeul ovani amplitudis mqone tal Ra, romelic  $OX$  RerZis gaswvri vrcel deba da pol arizebul ia  $OY$  RerZis gaswvri. naxazze 1.3.6 moyvanilia gadasxivebul i simZl avris damokidebul eba  $kR=2\pi R/\lambda$  sidideze or gansxvavebul SemTxvevaSi, rodesac rgol ebis Ria seqtoris  $\alpha$  kuTxe Seadgens  $15^\circ$  da  $30^\circ$ .

gadasxivebul i simZl avre iqna napovni poitingis veqtoris integriribiT ganxil ul i el ementis garSemo agebul i sferos zedapiris gaswvri. am grafikis pikebi Seesabamebian rezonansis SemTxvevas, radgan rezonansul sixSireebze aRznebul i denis amplituda izrdeba da Sesabamisad izrdeba gadasxivebul i simZl avre. gansxvaveba gadasxivebul i simZl avrebs Soris am or SemTxvevaSi Cndeba meore ( $kR=9.75$ ) da mesame ( $kR=12.8$ ) rezonansul sixSireebze.

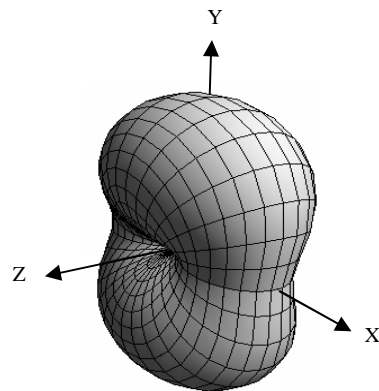


nax. 1.3.6 sixSirul i maxasiaTebel i

pirvel i rezonansis dros gadasxivebul i vel i 5, 6-jer ufro maRal ia. aq adgil i aqvs ormag rezonanss, radgan el ementi or nawil isgan Sedgeba. amiT aixsneba is, Tu ratom aris pirvel i rezonansi ufro farTo vidre danarCeni rezonansebi.



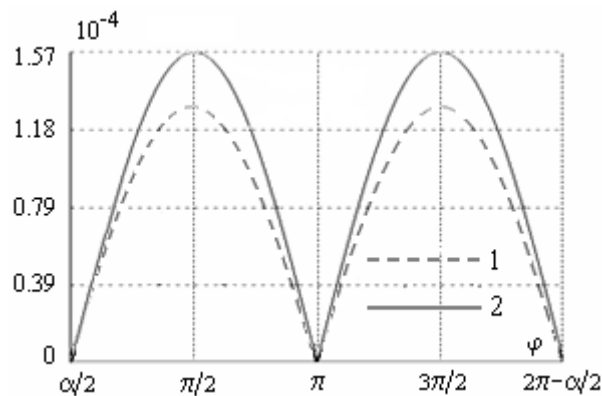
naxazze 1.3.7 moyvanil ia ganxil ul i el ementis mier gadasxivebul i vel is diagrama, rodesac mas ecema rezonansul i sixSiris mqone brtyel i tal Ra. moyvanil ia aseve Sesabamisi parametrebi.



gare rgol is radiusi -  $R$   
 Sida rgol is radiusi -  $0.5R$   
 Ria seqtoris kuTxe -  $15^\circ$   
 $kR=2.06$

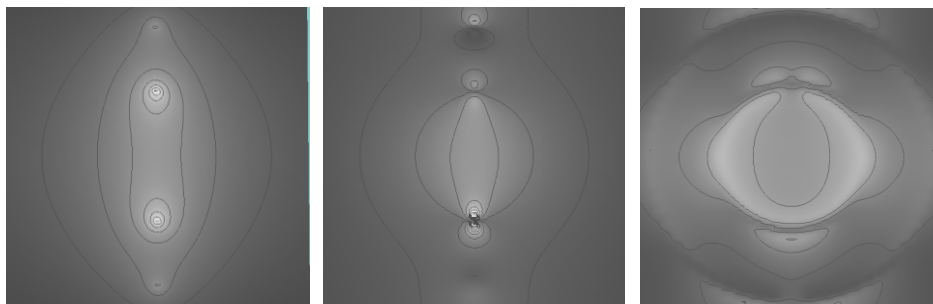
nax. 1.3.7 Sori vel is diagrama rezonansul sixSireze

ganxil ul el ementis maRal i vargisianoba gaaCnia. sixSiris cvl il ebiT rezonansis maxl obl ad, Segvl iZl ia gavzardoT an SevamciroT denis ampl ituda gare an Sida rgol Si. Semdeg naxazze (nax. 1.3.8) moyvanil ia is SemTxveva, rodesac ufro maRal i ampl itudis deni aRiZvrebA Sida rgol Si.



nax. 1.3.8 denebis ganawil eba el ementis rgol ebSi

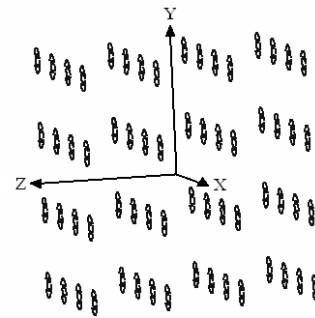
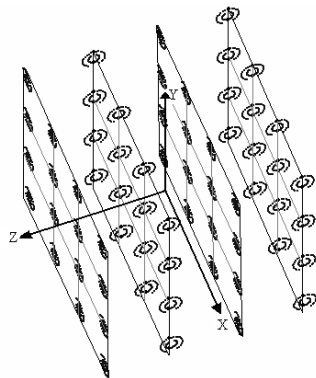
es aseve kargad Cans 1.3.9 naxazze sadac moyvanil ia axl o vel is ganawil eba rezonansul sixSireze a)  $XOZ$ , b)  $XOY$ , da g)  $YOZ$  si brtyeebSi. Sida rgol is garSemo ufro maRal i vel i formirdeba.



a) b) g)

nax. 1.3.9 axl o vel is ganawil eba a)  $XOZ$ , b)  $XOY$  da g)  $YOZ$  si brtyeebSi

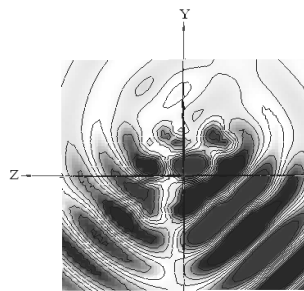
Semdeg ganxil ul ia aseTi tipis el ementebisagan Semdgari periodul i struqtorebi Tavisufal sivrceSi, el ementebis gansxvavebul i orientaciis dros (nax. 1.3.10, 1.3.11).



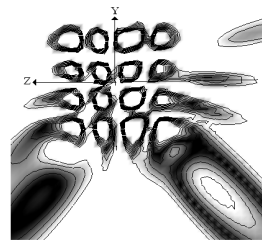
nax. 1.3.10 mesris periodebi:  $d_1 = d_2 = d_3 = 0.5\lambda$ ,  
rgol ebis radiusebi:  $R = 0.08\lambda$ ,  $r = 0.04\lambda$

nax. 1.3.11 mesris periodebi:  $d_1 = d_2 = d_3 = 0.8\lambda$ ,  
rgol ebis radiusebi:  $R = 0.14\lambda$ ,  $r = 0.07\lambda$

manZil i el ementebis Soris Seesabameba ormag rezonanss da el ementebis raodenobaa 4x4x4. aseTi tipis struqtorebi kompl eqsur Tvisebebs amJRavneben. naxazebi 1.3.12 a) da b) gviCvenebs axl o vel is ganawil ebas am ori gansxvavebul i struqturis SemTxvevaSi.



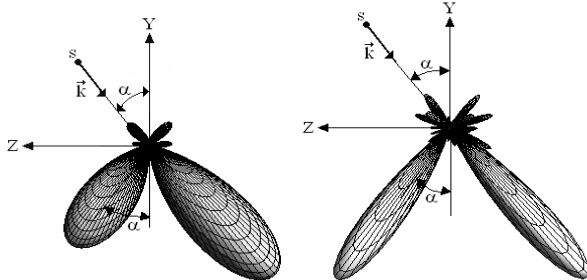
a)



b)

nax. 1.3.12 axl o vel is ganawil eba a) 1.3.10 da b) 1.3.11 geometriis SemTxvevaSi

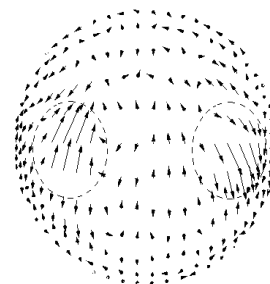
Semdeg moyvanil ia ganxil ul i struqtorebis mier gamosxivebul i Sori vel is diagramebi (nax. 1.3.13 a) da b)). rogorc vxedavT, orive SemTxvevaSi miReba ori didi ZiriTadi foTol i. erT maTgans gaaCnia dacemul i vel is mimaRTul eba, xol o meore foTol i Seesabameba uaryofiT gardatexas.



a)

b)

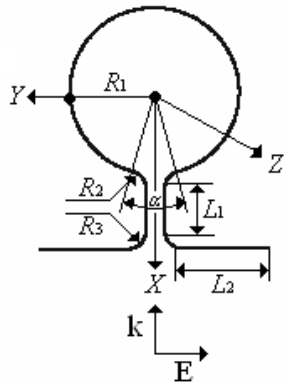
nax. 1.3.13 Sori vel is diagrama a) 1.3.10 da b) 1.3.11 geometriis SemTxvevaSi



nax. 1.3.14 vel is veqtorebis ganawil eba sferul zedapirze

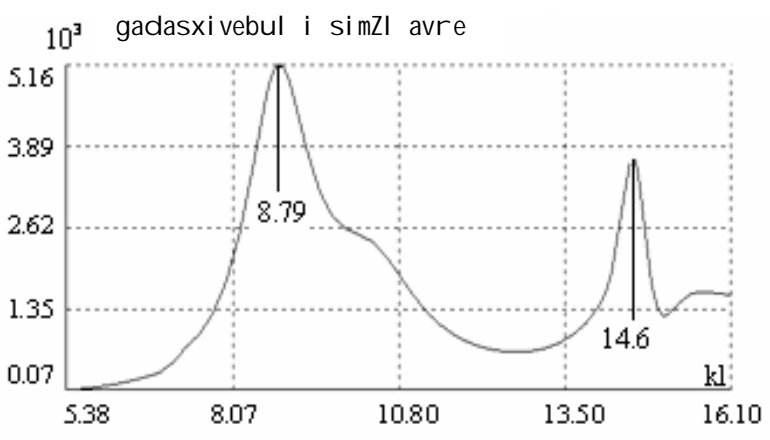
gabneul i vel is pol arizaciul i Tvisebebis Seswavl am gviCvena, rom am ZiriTadi foTI ebis gaswvri mas gaaCnia urTierTsawinaaRmdego mbrunavi pol arizacia (nax. 1.3.14). es ukanasknel i ufro ukeTesad Cans kompiuterul i animaciis dros.

**$\Omega$  el ementis zogierTi el eqtrodinamikuri Tvisebebis gamokvl eva.** qveviT moyvanilia sxva rezonansul i el ementis gamokvl evis Sedegebi. el ementi warmoadgens wvriL gamtars da gaaCnia berZnul i aso  $\Omega$  forma. ganxil eba SemTxvevebi rodesac igi imyofeba Tavisufal sivrceSi da aseve sasrul i zomebis mqone diel eqtriksi. aseTi saxis el ementis ganxil va saintereso imiT, rom mis bazaze SeiZl eba SeiQmnas mimarTul i gamosxivebis mqone antenuri mowyobil oba. amastanave aseTi el ementi saintereso imitom, rom Tu dacemul i vel i pol arizebul ia el ementis horizontal uri "fexebis" gaswvri, maSin mis momrgval ebul nawil Si maRal i amplitudis deni aRizvrebA. es deni aCens maRal  $\vec{H}$  magnitur da Sesabamisad maRal  $\vec{E}$  el eqtrul vel ebs. es  $\vec{E}$  da  $\vec{H}$  vel ebi urTierTmarTobul ni arian. Tu saTanadod SevarCevT  $\Omega$  el ementis parametrebs maSin igi hiugensis gamomsxivebel is msgavsi iqneba. naxazze 1.3.15 moyvanilia  $\Omega$  el ementis geometria da aseve misi parametrebi, romel nic iyvnen SerCeul ni farTo sixSirul i maxasiaTebel is misaRebad (nax. 1.3.16).



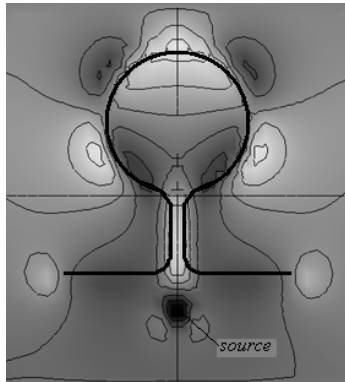
$l$  - el ementis srul i sigrZe  
 $R_1 = 0.1l, R_2 = 0.02l, R_3 = 0.02l,$   
 $L_1 = 0.05l, L_2 = 0.1l, \alpha = \pi/12$

nax. 1.3.15  $\Omega$ - el ementi da misi parametrebi

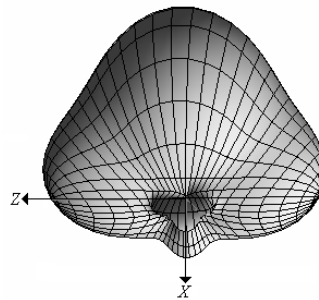


nax. 1.3.16 gadasxivebul i simZl avris damokidebul eba  $kl$  sidi deze

Semdeg naxazebze moyvanilia axl o vel is ganawil eba da Sori vel is diagrama rodesac dacemul i vel is wertil ovani gamomsxivebel i el ementis maxl obl ad imyofeba (nax. 1.3.17, 1.3.18). imisaTvis, rom avaridoT Tavi vel is singular arobebs el ementis gaswvri, vel is daxatvis sibrtye mcire manZil iTaa daSorebul i el ementis sibrtiyisgan. Sori vel is diagrama gviCvenebs, rom gadasxivebul i energiis umetesi nawil i erTi mimarTul ebiT vrcel deba.

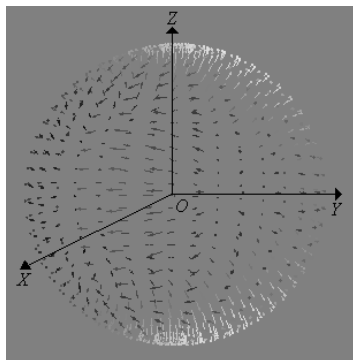


nax. 1.3.17 axl o vel is ganawil eba omega el ementis SemTxvevaSi

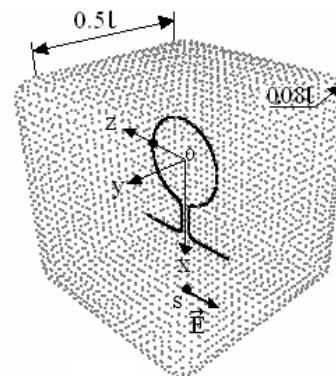


nax. 1.3.18 Sori vel is diagrama

Semdeg moyvanil ia gabneul i vel is pol arizaciis ganawil eba sferul zedapirze Sor zonaSi (nax. 1.3.19). misma anal izma gviCvena, rom gabneul vel s garkveul i mimarTul ebebiT gaaCnia el ifsuri da wriul i pol arizacia.



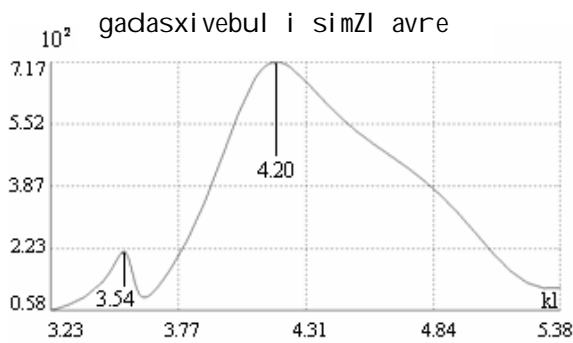
nax. 1.3.19 pol arizaciis ganawil eba Sor zonaSi



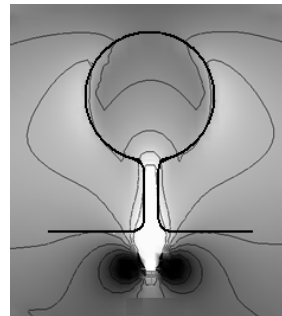
nax. 1.3.20  $\Omega$ -el ementi diel eqtrikul i kubis SigniT

imisaTvis rom miviRoT rezonansi ufro farTo sixSirul diapazonSi,  $\Omega$  el ementi ganxil eba  $\varepsilon=4$  SeRwevadobis mqone diel eqtrikis SigniT. diel eqtriks gaaCnia gl uvi kubis forma (nax. 1.3.20). dacemul i vel is wertil ovani wyaro am diel eqtrikis SigniT imyofeba.

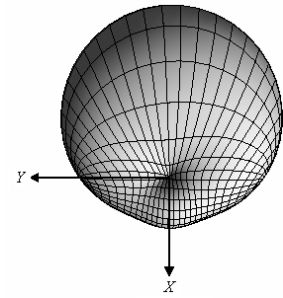
Semdeg naxazze moyvanil ia sistemis mier gadasxivebul i simZl avris damokidebul eba  $kl$  parametrze (nax. 1.3.21). farTo rezonansi  $kl=4.2$  mniSvnel obaze aris ormagi, anu warmoadgens rezonanss  $\Omega$  el ementsa da diel eqtriks Soris. naxazzebi 1.3.22 a) da b) gviCvneben axl o vel is ganawil ebas da Sori vel is diagramas. am SemTxvevaSi gamosxivebul vel s ar gaaCnia gamokveTil i mimarTul eba.



nax. 1.3.21 gadaxivebul i simZl avris  
damokidebul eba kl sidi deze  
diel eqtrikis SemTxvevaSi



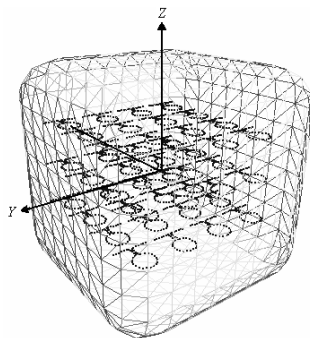
a)



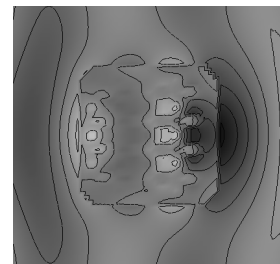
b)

nax. 1.3.22 a) axl o vel is ganawil eba,  
b) Sori vel is diagrama

Semdeg ganxil ul iqna  $\Omega$  el ementebisagan Semdgari samganzomil ebiani periodul i meseri, romel ic iyo moTavsebul i diel eqtrikSi (nax. 1.3.23). el ementebis raodenoba meserSi tol ia  $4 \times 4 \times 3$  da manZil i maT Soris udris  $4R_1$ , sadac  $R_1$  omega el ementis rgol is radiusia. naxazze 1.3.24 moyvanil ia axl o vel is ganawil ebas  $XOZ$  sibrtyeSi. rogorc Cans energiis umetesi nawil i garkveul i mimarTul ebiT vrcel deba.

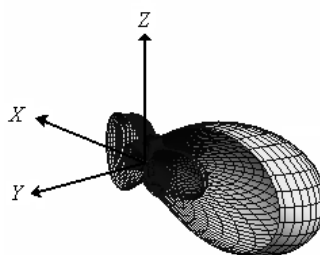


nax. 1.3.23 omega el ementebisagan  
Semdgari meseri diel eqtrikSi



nax. 1.3.24 axl o vel is  
ganawil eba  $XOZ$  sibrtyeSi

naxazze 1.3.25 moyvanil ia Sori vel is diagrafemebis Sedareba rodesac gagvaCnia 1 da  $4 \times 4 \times 3$   $\Omega$  el ementi. gadaxivebul i vel is maqsimal uri mniSvnel oba  $4 \times 4 \times 3$  el ementis SemTxvevaSi gacil ebiT ufro metia radgan yovel i el ementi rezonansSi imyofeba da Sedegad miReba maTi vel ebis superpozicia.

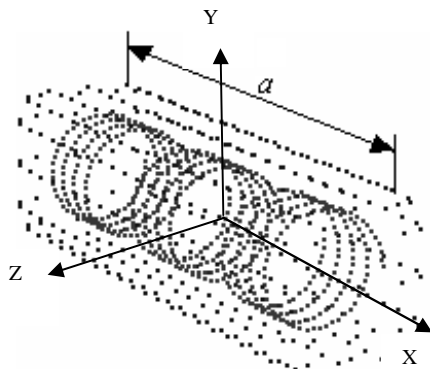


nax. 1.3.25 Sori vel is diagrama 1 da  
 $4 \times 4 \times 3$  el ementebis SemTxvevaSi

**spiral ebisgan Semdgari metal o - diel qtrikul i struqturebi.**

Semdeg gamokvl eul ia iseTi struqtura, romel sac SeuZl ia wrfivad pol arizebul i tal Ra gardaqmnas el ifsurad pol arizebul Si. amastanave mis mier gamosxivebul vel s gaaCnia brtyel i diagrama garkveul i sxoul ovani kuTxis fargl ebSi [38, 39] (SedarebiT ufro adre ganxil ul iqna aseTi amocanis organzomil ebiani SemTxveva [40]). struqtura warmoadgens sam spiral s6 romel nic imyofebian diel eqtrikSi. ganxil eba ori SemTxveva: pirvel SemTxvevaSi diel eqtriks gaaCnia cil indris forma da orive mxridan SemosazRvrul ia naxevarsferoebiT. meore SemTxvevaSi diel eqtriks gaaCnia paral el epipedis forma. dacemul i vel is kombinirebul i gamomsxivebel i imyofeba struqturis SigniT erTerTi spiral is maxl obl ad.

Semdegi naxazi gviCvenebs struqturis geometrias paral el epipedis fromis SemTxvevaSi (nax. 1.3.26 a)). aq aseve moyvanil ia parametrebis is mniSvnel obebi, rodesac am struqturas gaaCnia zemoaRniSnul i Tvisebebi (nax. 1.3.26 b)).



a)

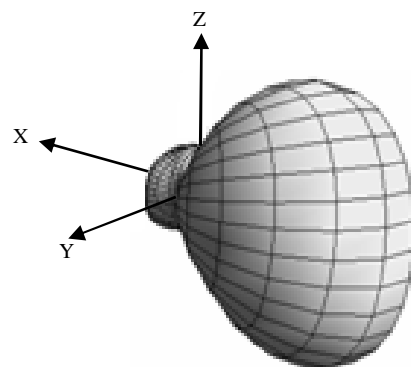
diel eqtrikul i paral el epipedis zomebi  $X, Y, Z$  RerZebis gaswrviv:  $a \times 0.25a \times 0.25a$ ; diel eqtrikis kuTxeebis momrgval ebis radiusi  $0.055a$ ; diel eqtrikul i SeRwevadoba 4; tal Ris sigrZe diel eqtrikis gareT  $a$ ; spiral is simaRl e  $0.18a$ ; spiral is radiusi  $0.09a$ ; manZil i spiral ebs Soris  $0.32a$ ; spiral ebis raodenoba 3; kombinirebul i dipol is koordinata  $X$  RerZze -  $0.43a$ ; kombinirebul i dipol is pol arizacia:  $Y$  - el eqtrul i dipol isaTvis,  $Z$  - magniturisaTvis.

b)

nax. 1.3.26 a) struqturis geometria, b) struqturis parametrebi



a)



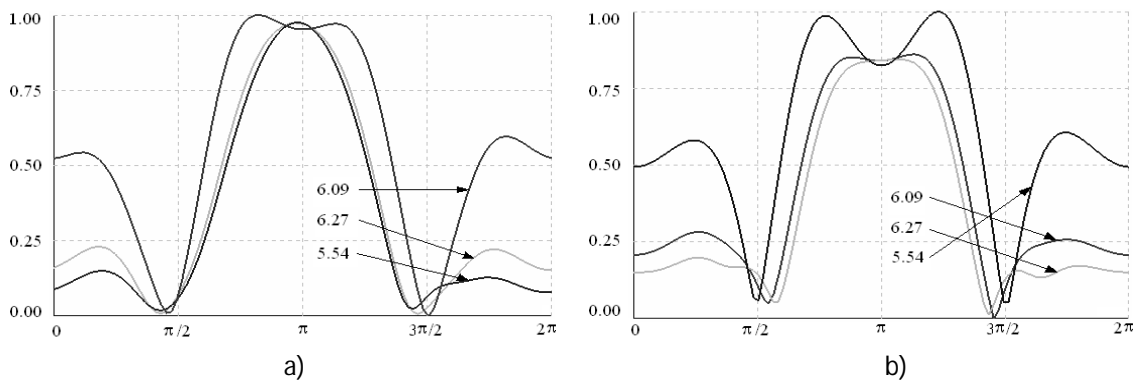
b)

nax. 1.3.27 a) struqturis sixSirul i maxasiaTebel i, b) Sori vel is diagrama

naxazze 1.3.27 a) moyvanil ia ganxil ul i struqturis mier gadasxivebul i simZl evaris damokidebul eba  $ka$  parametrze. am parametris

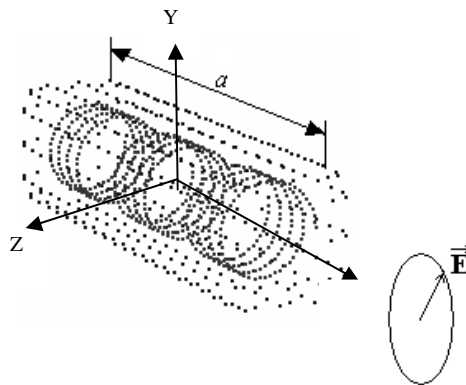
moyvanil fargl ebSi, struqturas gaaCnia ori rezonansi. pirveli rezonansi metad viwroa da amitom interest meore rezonansi waroadgens, rodesac  $ka=6.09$ . naxazze 1.3.27 b) moyvanil ia Sori vel is diagrama meore rezonansis SemTxvevaSi. ganxil ul i struqturis mier gamosxivebul i energiis ZiriTadi nawili vrcel deba  $OX$  RerZis sawinaaRmdego mimarTul ebiT.

Semdeg moyvanil ia Sori vel is diagrama or urTierTmarTobul sibrtyeSi rezonansis dros da aseve mis maxl obl ad (nax. 1.3.28 a), b)). mniSvnel obebi danormirebul ia maqsimal ur mniSvnel obaze. rogorc Cans ganxil ul i struqturis mier gamosxivebul vel s gaaCnia erTi da igive ampl ituda garkveul kuTxur diapazonSi da am diapazonSi Sori vel is diagrama brtyel ia.



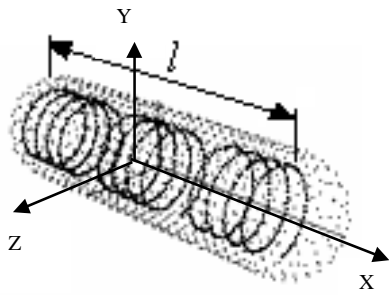
nax. 1.3.28 Sori vel is diagrama a)  $XOY$  da b)  $XOZ$  sibrtyeSi

rezonansul sixSireebze diel eqtriksi moTavsebul spiral ebSi aRiZvreba maRal i ampl itudis denebi, ris Sedegadac gabneul vel s el ifsur i pol arizacia gaaCnia (nax. 1.3.29).



nax. 1.3.29 el ifsurad pol arizebul i tal Ra struqturis gareT

Semdeg ganxil ul iqna SemTxveva, rodesac diel eqtriks cil indrul i forma gaaCnia. naxazze 1.3.30 moyvanil ia ganxil ul i struqturis geometria da misi parametrebis mniSvnel obebi, rodesac mas anal ogiuri Tvisebebi gaaCnia.



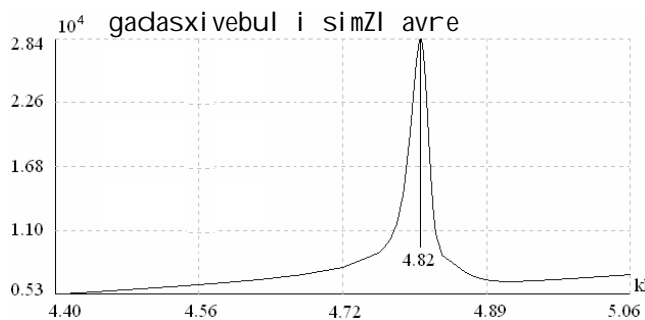
a)

diel eqtrikul i cil indris radiusi  $0.183l$ ; diel eqtrikul i SeRwevadoba 4; tal Ris sigrze diel eqtrikis gareT  $0.183l$ ; spiral is simaRl e  $0.27l$ ; spiral is radiusi  $0.13l$ ; manZil i spiral ebs Soris  $0.4l$ ; spiral ebs raodenoba 3; kombiniirebul i dipol is koordinata  $OX$  RerZze:  $0.67l$ ; kombiniirebul i dipol is pol arizacia:  $Y$  - el eqtrul dipol isaTvis,  $Z$  - magnituri dipol isaTvis

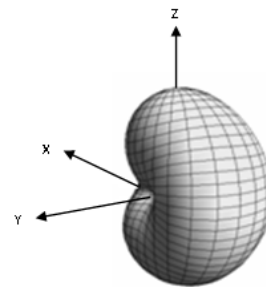
b)

nax. 1.3.30 a) struqturis geometria, b) struqturis parametrebi

Semdegi naxazi gviCvenebs gadasxivebul i simZl avris damokidebul ebas  $kl$  parametrze, sadac  $l$  cil indris simaRl ea (nax. 1.3.31). ganxil ul i struqturis Tvisebebi Sesawavl il ia  $kl=4.82$  rezonansis maxl obl ad. aq aseve moyvanil ia Sori vel is diagrama rezonansul sixSireze (nax. 1.3.32). rogorc Cans gadasxivebul i vel is energiis ZiriTadi nawil i vrcel deba garkveul i mimarTul ebiT, xol o mis sawinaaRmdego mimarTul ebiT vel i faqtiurad qreba.

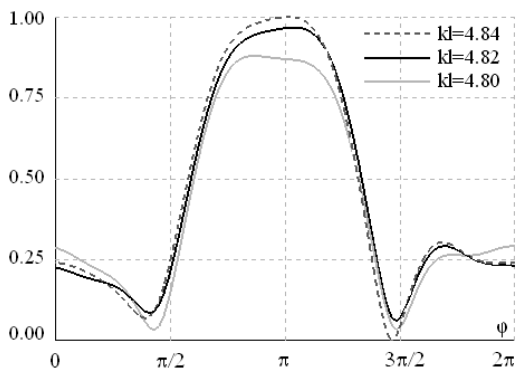


nax. 1.3.31 sixSirul i maxasiaTebel i

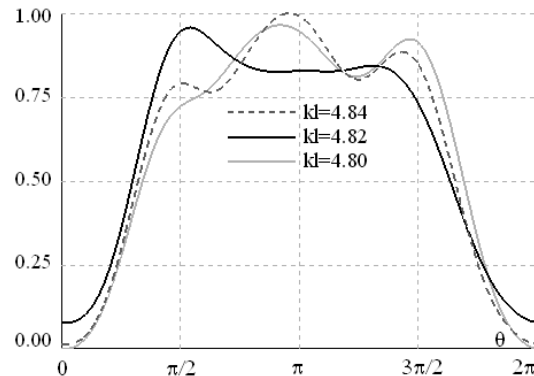


nax. 1.3.32 Sori vel is diagrama

Semdeg naxazze moyvanil ia Sori vel is diagrama or urTierTmarTobul sibrtyeSi rezonansis SemTxvevaSi da aseve rezonansis maxl obl ad (nax. 1.3.33). rogorc Cans, Sor zonaSi vel s gaaCnia Tanabari ampl itudis mniSvnel obebi garkveul kuTxur diapazonSi da Sesabamisad sakmaod brtyel i diagrama.



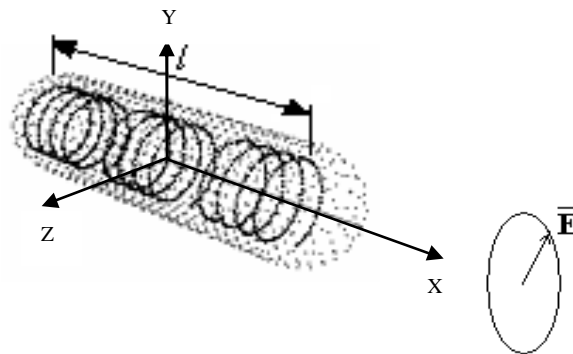
a)



b)

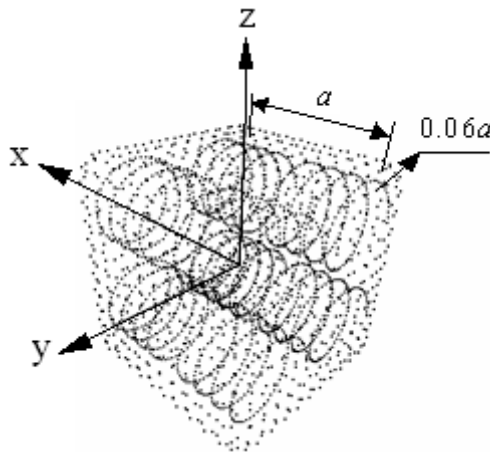
nax. 1.3.33 Sori vel is diagrama a)  $XOY$  da b)  $XOZ$  sibrtyeSi





max. 1.3.34 el ifsurad pol arizebu, i  
tal Ra struqturis gareT

rezonansis SemTxvevaSi, denis ampl ituda spiral ebSi mkveTrad izrdeba da mTel i struqturis mier gamosxivebul vel s el ifsuri pol arizacia gaaCnia (max. 1.3.34).



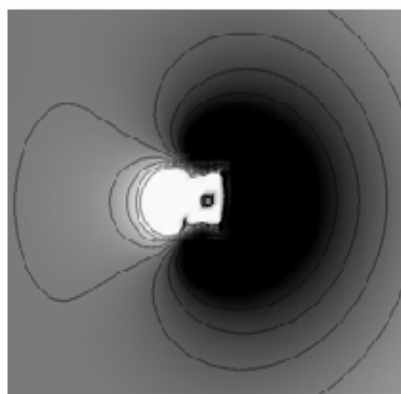
spiral is radiusi  $0.2a$ ;  
spiral ebis raodenoba 8;  
spiral is simaRI e  $0.4a$   
manZil i spiral ebs Soris  $0.5a$

a)

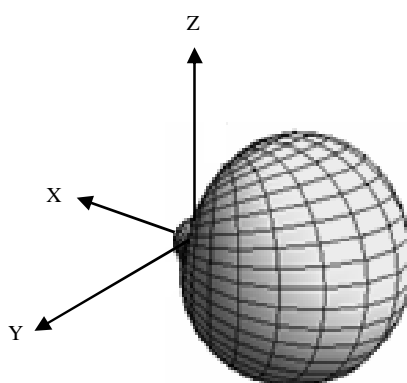
b)

max. 1.3.35 a) struqturis geometria, b) struqturis parametrebi

Semdeg iqna ganxil ul i periodul i meseri, romelic Sedgeba  $2 \times 2 \times 2$  spiral isagan da aris moTavsebul i gl uvi diel eqtrikul i kobis SigniT, roml is SeRwevadobaa  $\epsilon = 4$  (max. 1.3.35). dacemul i vel is kombinirebul i wyaro imyofeba diel eqtrikis centrSi da asxivebs  $OX$  RerZis sawinaaRmdego mimarTul ebiT. gamosxivebul vel s gaaCnia mbrunavi pol arizacia da axl osaa wriul Tan. qvemoT moyvanilia axl o vel is ganawil eba da Sori vel is diagrama marTkuTxa sakoordinato sistemaSi (max. 1.3.36 da 1.3.37). rogorc vxedavT, diagramas gaaCnia II asos forma didi sxgul ovani kuTxis fargl ebSi. energiis umetesi nawil i vrcel deba mxol od erT naxevarsivrceSi.

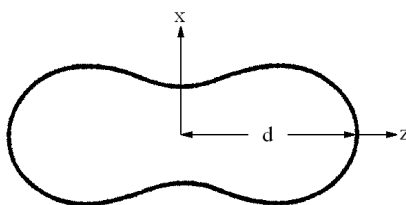


max. 1.3.36 axl o vel is ganawil eba  $XOZ$  sibrtyeSi



max. 1.3.37 Sori vel is diagrama

**kasinis el ementis SemTxveva.** aq ganixil eba SemTxveva rodesac mesris el ements kasinis oval is forma gaaCnia (max. 1.3.38) [41, 42].



max. 1.3.38 kasinis el ementi

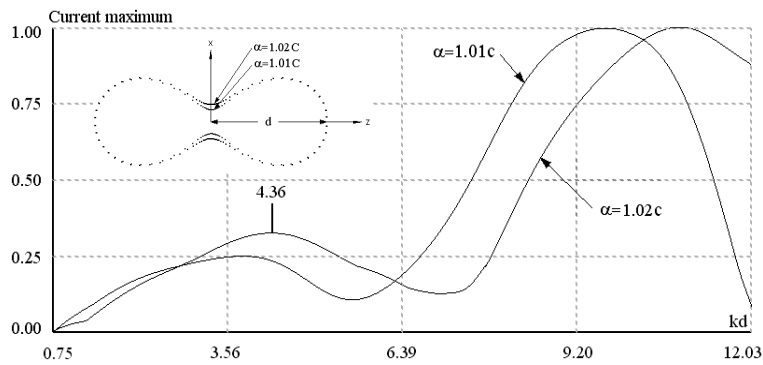
pol arul koordinatebSi am mrudis gantol ebaa

$$\rho(\varphi) = \sqrt{c^2 \cos 2\varphi + \sqrt{a^4 - c^4 \sin^2 2\varphi}},$$

sadac  $c$  fokusebis Soris manZil is naxevaria, xol o  $a$  garkveul i ricxvia. Cven ganvixil avT SemTxvevas, rodesac srul deba utol oba  $c < a < \sqrt{2}c$  da kasinis mruds oTxi gadaRunvis wertil i gaaCnia.

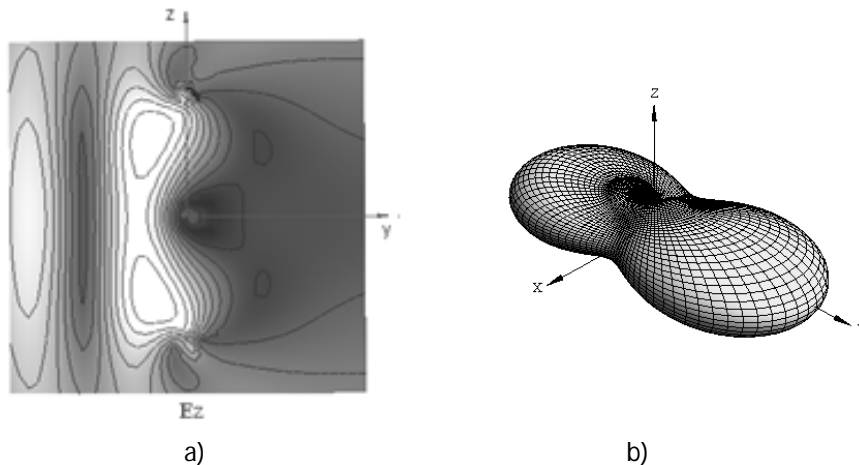
aseTi saxis el ementis ganxil va sainteresoa imiT, rom mas farTo rezonansebi gaaCnia. es xel s Seuwyobs Sesabamisi struqturebis kompl eqsuri Tvsebebis gamovl enas farTo sixSirul diapazonSi.

**erTi el ementis SemTxveva brtyel i dacemul i tal Ris dros.** el ementi imyofeba  $XOZ$  sibrtyeSi, dacemul i vel i warmoadgens brtyel tal Ras, romel ic vrcel deba  $OY$  RerZis gaswvriV da gaaCnia orive  $OX$  da  $OZ$  pol arizacia. qvemoT moyvanil i suraTi gviCvenebs aRZrul i denis danormirebul i maqsimis damokidebul ebas  $kd$  parametrze, sadac  $k$  tal Ruri ricxvia, xol o  $d$  warmoadgens kasinis maqsimal ur radiuss (max. 1.3.39). aq moyvanilia ori gansxvavebul i mrudi, roml ebic Seesabamebian el ementis sxvadasxva geometrias ( $a=1,01c$  da  $a=1,02c$ ). am mrudebis maqsimumebi miuTITeben rezonansis SemTxvevas.  $a$  koeficientis umniSvel o gazrdam gamoiwvia rezonansis wanacvl eba marj vniv.



ნახ. 1.3.39 გადასხვივების სიმაღლის ავრის დამოკიდებულება  $kd$  პარამეტრზე

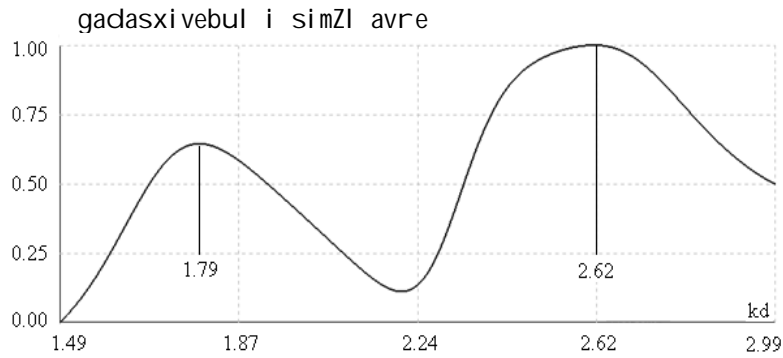
სამდეგ მოყვანილია ახლო ველის  $E_z$  კომპონენტის განაწილება  $YOZ$  სიბრტყეში და ასევე სორის ველის დიაგრამა რეზონანსის შემთხვევაში, როდესაც  $kd=4.36$ ,  $a=1.02c$  (ნახ. 1.3.40 ა) და ბ)).



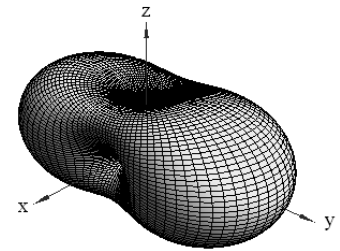
ნახ. 1.3.40 ა) ახლო ველის განაწილება, ბ) სორის ველის დიაგრამა

გრაფიკის სამდეგი პიკი მარალი რიგის რეზონანსს უარმოდგენს და სორის ველის დიაგრამას მრავალი ფოტოლი გააჩნია. ველის ტვიხეხეხის გამოკვლევამ გვიჩვენა, რომ მასელი ფსური პოლარიზაცია გააჩნია და ელიფსობის კოეფიციენტია 1:2.5.

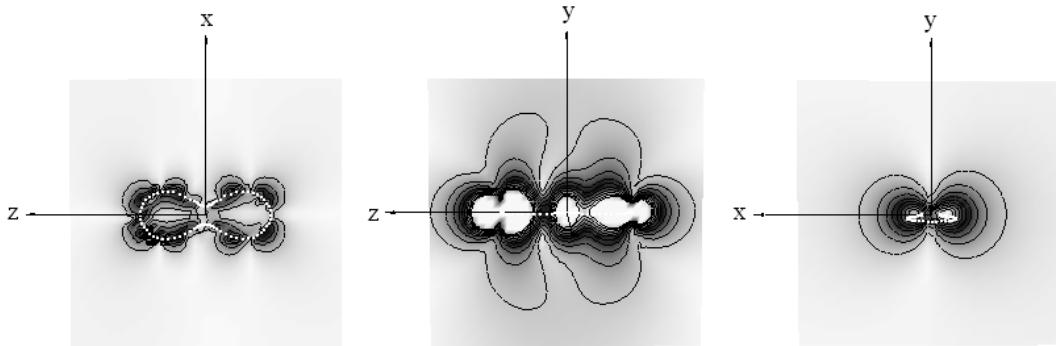
**ერთი ელემენტის შემთხვევა როდესაც ველის ოვანი დაცემული ველის უყარო მასთან ახლოს იმყოფება.** ელემენტი კვლავ  $XOZ$  სიბრტყეში იმყოფება. მასეცა  $X$  პოლარიზაციის მომენტის  $R_a$ , რომლის ველის ოვანი გამოხსვივებელი იმყოფება ველის  $(0, -3d, 0)$ . ღვეტი მოყვანილია დანორმირებული გადასხვივების სიმაღლის ავრის დამოკიდებულება  $kd$  სიდიდეზე (ნახ. 1.3.41). მოყვანილი ფარგლებში ცხვენ ვხედავთ ორ პიკს, რომელიც რეზონანსს შესაბამისად გამოკვლევით ორივე რეზონანსი. აგრამოყვანილი სორის ველის დიაგრამა (ნახ. 1.3.42) და ახლო ველის  $E_z$  კომპონენტის განაწილება როდესაც  $kd=1.79$  (ნახ. 1.3.43). როგორც ვხედავთ, გამოკვლევით ენერჯის გავრცელების ორი მიმართულება  $-OY$  რეზონანსის გასვრივ და მის საპირაპირედგოდ.



nax. 1.3.41 gadasxivebul i simZI avris damokidebul eba  $kd$  si di deze

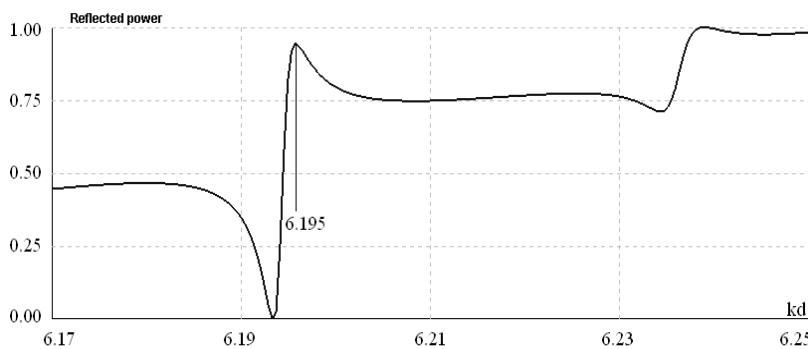


nax. 1.3.42 Sori vel is diagrama

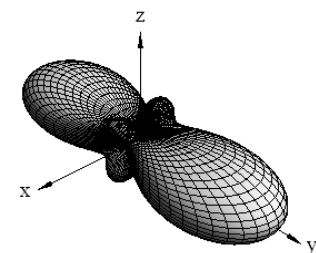


nax. 1.3.43 axl o vel is ganawil eba

meore SemTxvevaSi, rodesac  $kd=2.62$ , diagramaSi SeimCneva bevri foTol i radgan es ufro maRal i rigis rezonansia.



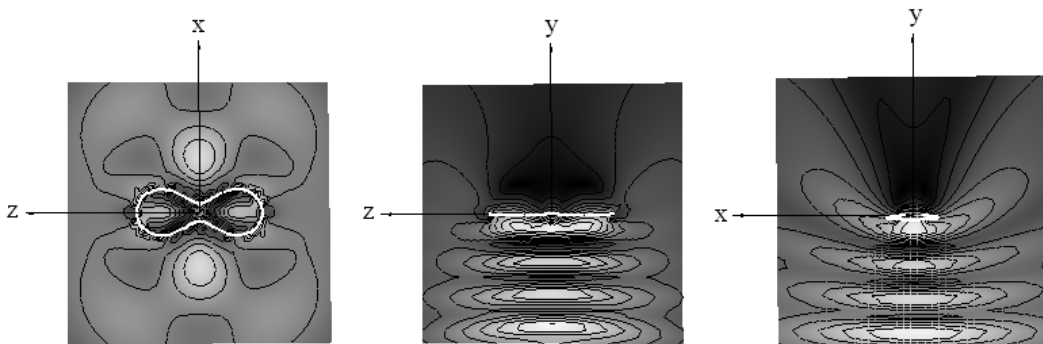
nax. 1.3.44 gadasxivebul i simZI avris damokidebul eba  $kd$  si di deze



nax. 1.3.45 Sori vel is diagrama

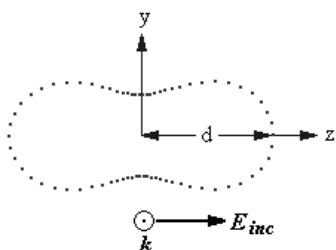
Semdeg ganxil ul iqna SemTxveva, rodesac dacemul i vel is wyaro imyofeba  $(0, -3d, 0)$  wertil Si da gaaCnia Z pol arizacia. qveiT moyvanil ia danormirebul i gadasxivebul i simZI avris damokidebul eba  $kd$  si di deze (nax. 1.3.44). gamoTvl ebi gviCvenebS, rom X pol arizaciis SemTxvevisagan gansxvavebiT, aq gadasxivebul i simZI avre erTi rigiT ufro maRal i

gamodis. rogorc moyvanil i grafiki gviCvenebs, SemTxveva  $kd=6.195$  Seesabameba rezonanss. qveviT moyvanil ia Sori vel is diagrama (nax. 1.3.45) da axl o vel is ganawil eba (nax. 1.3.46) am rezonansis dros. aqac gamokveTil ia energiis gavr cel ebis ori mimarTul eba -  $OY$  RerZis gaswvri v da mis sawinaaRmdegod, Tumca  $X$  pol arizaciisagan gansxvavebiT es energia metad ufro mimarTul ia.

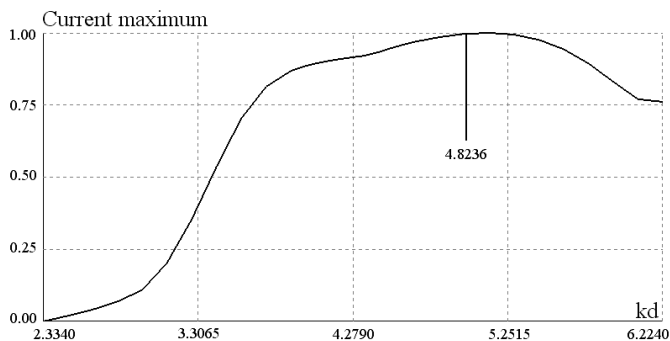


nax. 1.3.46 axl o vel is ganawil eba

**ganieri rezonansis SemTxveva.** Tu Sevcl iT kasinis el ementis formas, maSin SegviZl ia miviRoT ufro ganieri rezonansi. naxazze 1.3.47 moyvanil ia el ementis geometria, rodesac mis parametrebs Soris arsebobs damokidebul eba ( $a=1.1c$ ). dacemul i vel is wyaro imyofeba wertil Si ( $4d, 0, 0$ ).

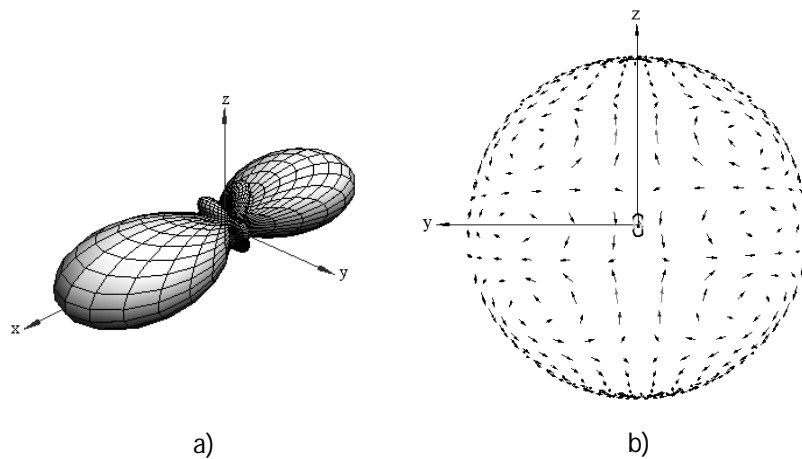


nax. 1.3.47 el ementis geometria

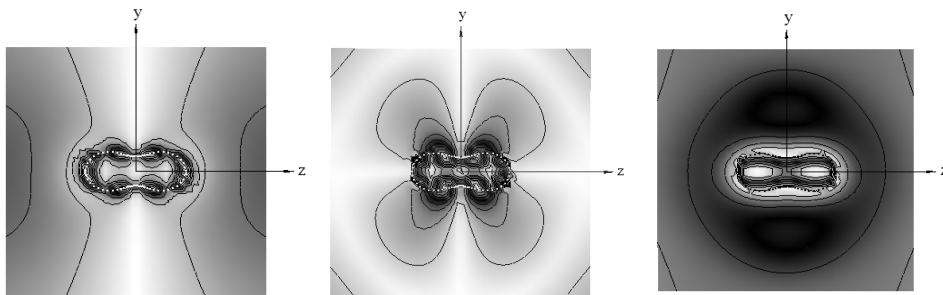


nax. 1.3.48 denis maqsimumis damokidebul eba  $kd$  parametrze

dacemul i vel i vrcel deba  $OX$  RerZis sawinaaRmdego mimarTul ebiT da gaaCnia  $OZ$  pol arizacia. areSi  $kd=2.3340-6.2240$ , el ementis gaaCnia ganieri rezonansi (nax. 1.3.48). Semdeg naxazze moyvanil ia Sori vel is diagrama rezonansis dros (nax. 1.3.49 a). am SemTxvevaSi vel s mbrunavi pol arizacia gaaCnia (nax. 1.3.49 b)) rac ufro ukeTesad Cans animaciisas. gabneul vel s gaaCnia ori didi foTol i. axl o vel is ganawil eba rezonansis dros moyvanil ia naxazze 1.3.50.

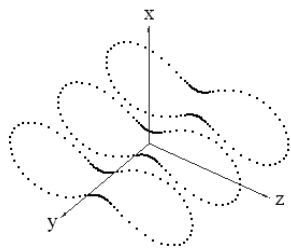


nax. 1.3.49. a) Sori vel is diagrama ( $kd=4.8236$ ), b) mbrunavi pol arizacia

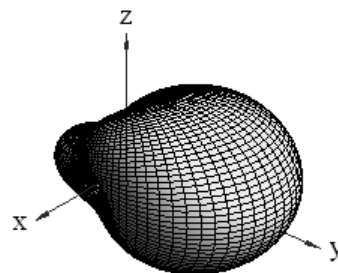


nax. 1.3.50 axl o vel is komponentebis ganawil eba

**sami el ementis SemTxveva rodesac dacemul i vel is wyaro maTTan axl os imyofeba.** ganixil eba sami kasini Tavisufal sivrceSi (nax. 1.3.51). dacemul i tal Ras  $X$  pol arizacia gaaCnia da misi wyaro imyofeba wertil Si  $(0, -3d, 0)$ .

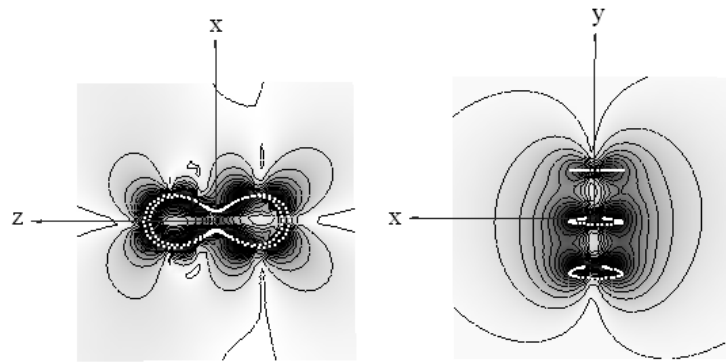


nax. 1.3.51 struqturis geometria

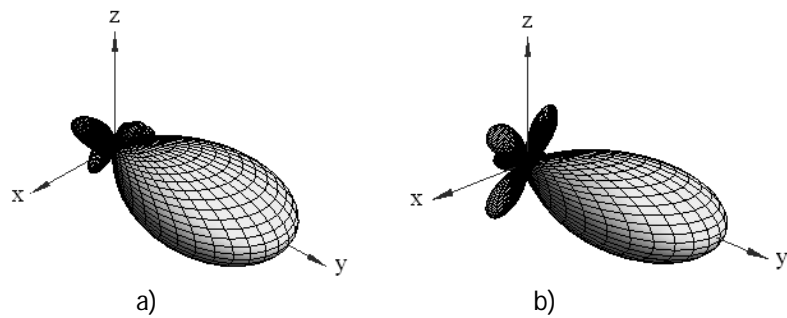


nax. 1.3.52 Sori vel is diagrama

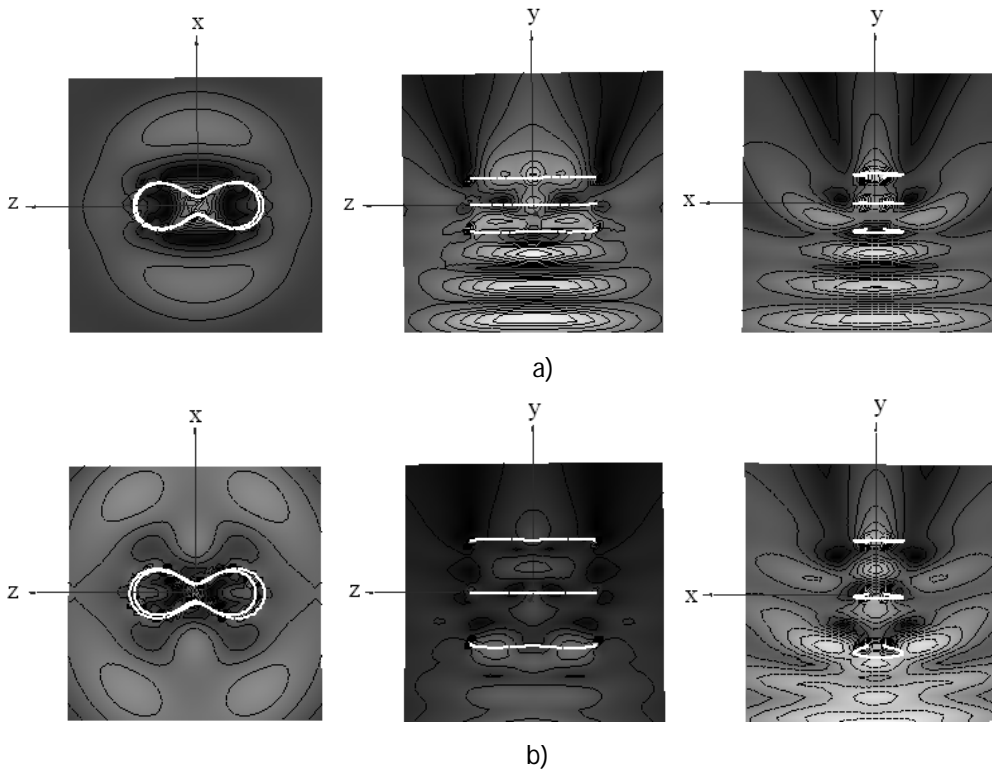
erTi kasinis rezonansul sixSireze ( $kd=1.79$ ) napovnia rezonansul i manZil i maT Soris, rodesac aqvs adgil i ormag rezonanss ( $d_2=0.714d$ ). naxazze 1.3.52, 1.3.53 moyvanil ia Sori vel is diagrama da axl o vel is ganawil eba. rogorc vxedavT, ormagi rezonansis dros gamosxivebul energias gaaCnia garkveul i mimarTul eba sivrceSi.



max. 1.3.53 axl o vel is ganawil eba



max. 1.3.54 Sori vel is diagrama a)  $d_2=0.04d$ , b)  $d_2=0.84d$

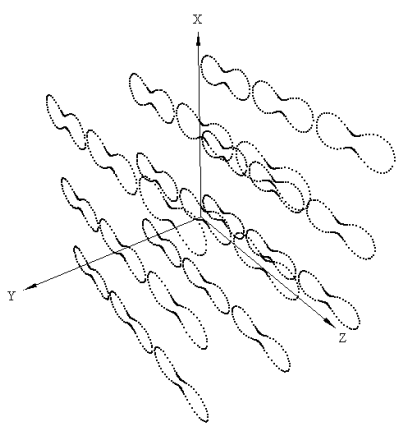


max. 1.3.55 axl o vel is ganawil eba a)  $d_2=0.04d$ , b)  $d_2=0.84d$

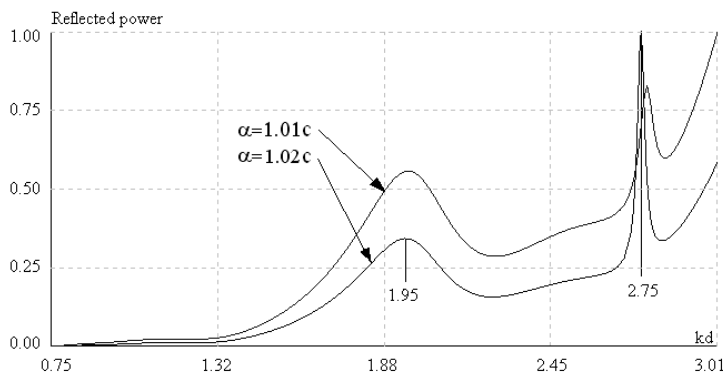
Z pol arizaciis dros, rezonansul sixSireze ( $kd=6.195$ ) kvl av napovnia optimal uri manZili i el ementebs Soris, rodesac aqvs adgili i

ormag rezonanss. am manZil is mniSvnel obaa  $d_2=0.04d$  da aseve  $d_2=0.84d$ . qveviT moyvanilia Sori vel is diagramebi da axl o vel is  $E_z$  mdgenel is ganawil eba am ori rezonansis SemTxvevaSi (nax. 1.354 a), b) da nax. 1.355 a), b)). rogorc vxedavT, ormagi rezonansis dros gadasxivebul i vel i ufro mimarTul ia.

**meseri Tavisufal sivrceSi.** Semdeg ganxil ul iqna kasinis el ementebisagan Semdgari periodul i meseri (nax. 1.356), romel sac  $OY$  mimarTul ebidan ecema brtyel i,  $OX$  da  $OZ$  pol arizaciebis mqone tal Ra. erTi el ementis rezonansul SemTxvevisaTvis ( $kd=4.36$ ) iqna napovni optimal uri manZil i ( $d_1=d_2=d_3=2.09d$ ) el ementebis Soris, rodesac aqvs adgili ormag rezonanss. naxazze 1.357 moyvanilia gadasxivebul i simZI avris damokidebul eba  $kd$  parametrze.

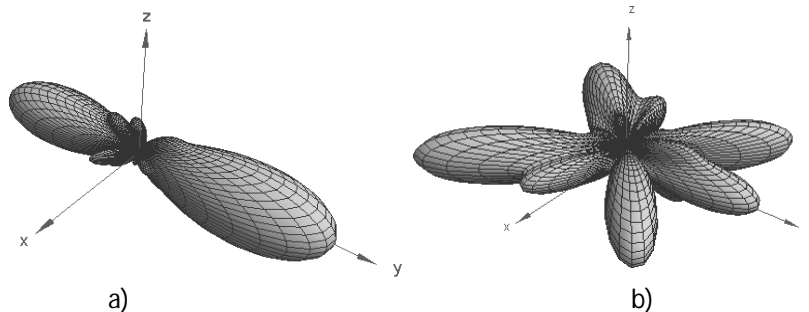


nax. 1.356 mesris geometria



nax. 1.357 gadasxivebul i simZI avris damokidebul eba  $kd$  parametrze

Cven vxedavT, rom wina SemTxvevisagan gansxvavebiT, kasinis  $a$  koeficientis cvl il ebiT rezonansis wanacvl eba ar xdeba. Semdeg moyvanilia Sori vel is diagrama da aseve axl o vel is  $E_z$  komponentis ganawil eba rezonansebis SemTxvevaSi, rodesac  $a=1,02c$ ,  $kd=1.95$  da  $kd=2.75$  (nax. 1.358 da 1.359).

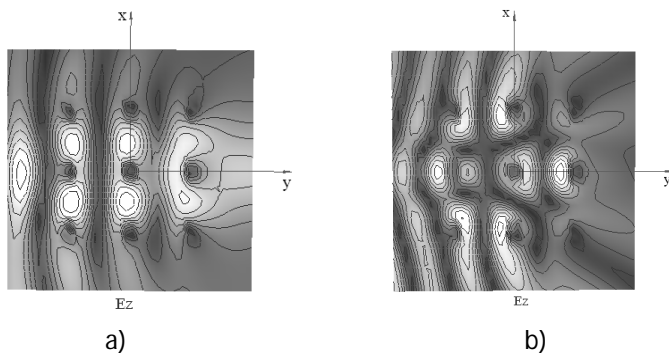


nax. 1.358 Sori vel is diagrama: a)  $kd=1.95$ , b)  $kd=2.75$

rezonansis dros, rodesac  $kd=1.95$ , gamosxivebul i vel i ZiriTadad  $OY$  RerZis gaswriv vrcel deba. Semdegi rezonansis dros ( $kd=2.75$ ),  $XOY$

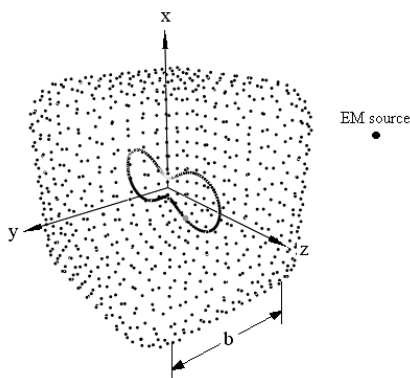


sibrtyeSi gamokveTil ia gabneul i vel is ramodenime mimaRTul eba. gabneul i vel is kvl evam gviCvena aseve, rom mas gaaCnia el ifsuri pol arizacia el ifsurobis koeficientiT 1:2.



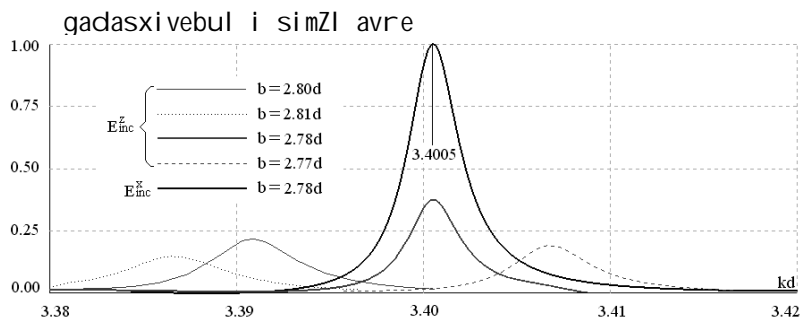
max. 1.3.59 axl o vel is ganawil eba: a)  $kd = 1.95$ , b)  $kd = 2.75$

**el ementi diel eqtrikis SigniT.** ganxil ul iqna SemTxveva rodesac erTi kasinis el ementi moTavsebul i iyo  $\epsilon = 4$  SeRwevadobis mqone diel eqtrikul i kubis SigniT (max. 1.3.60). dacemul i vel is wertil ovani wyaro imyofeba  $(0, -4d, 0)$  wertil Si.

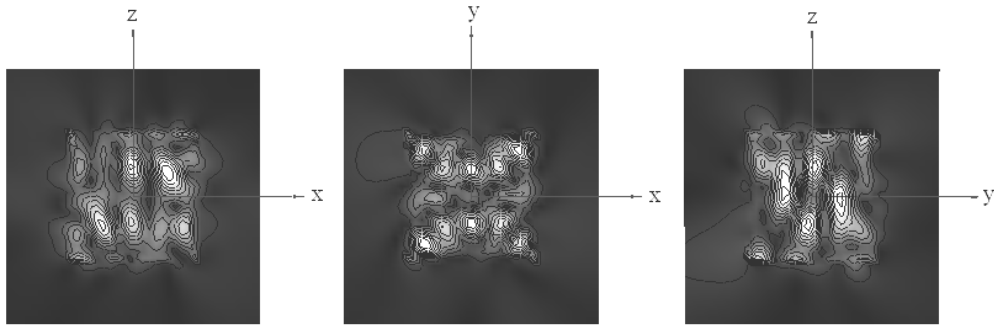


max. 1.3.60 kasinis el ementi diel eqtrikis SigniT

Semdeg naxazze (max. 1.3.61) moyvanil ia maqsimumze danormirebul i gadasxivebul i simZl avris damokidebul eba  $kd$  parametrze kubis sxvadasxva  $b$  zomis SemTxvevaSi. rogorc vxedavT, am simZl avris maqsimal uri mniSvnel oba (rezonansi el ementsa da diel eqtrikis Soris) miirweva rodesac  $kd = 3.4005$ , dacemul i vel is  $OX$  pol arizaciis SemTxvevaSi. axl o vel is ganawil eba am rezonansis SemTxvevaSi moyvanil ia naxazze 1.3.62.

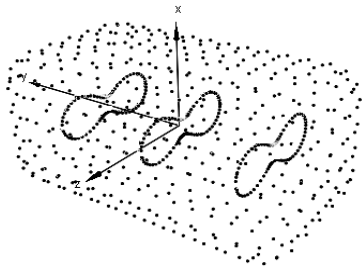


max. 1.3.61 gadasxivebul i simZl avris damokidebul eba  $kd$  parametrze

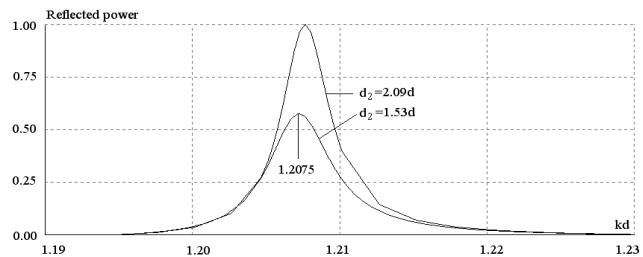


nax. 1.3.62 axl o vel is ganawil eba

**meseri diel eqtrikis SigniT.** aseve ganxil ul iqna SemTxveva rodesac sami kasinis el ementi moTavsebul i  $\varepsilon=4$  SeRwevadobis mqone diel eqtrikul paral el epipedSi (nax. 1.3.63). manZil i el ementebS Soris  $1.53d$ -s Seadgens. diel eqtrikis zomebia  $2.37d \times 2.79d \times 4.87d$  da SemosazRvrul ia gl uvi zedapiriT. momrgval ebis radiusia  $0.56d$ . naxazze 1.3.64 moyvanilia danormirebul i maqsimal ur mniSvnel obaze gadasxivebul i simZl avris damokidebul eba  $kd$  parametrze. aq moyvanilia ori mrudi, roml ebic Seesabamebian sxvadasxva manZil ebs el ementebS Soris. rogorc vxedavT, gadasxivebul i simZl avre izrdeba rodesac manZil i xdeba  $2.09d$ -s tol i.

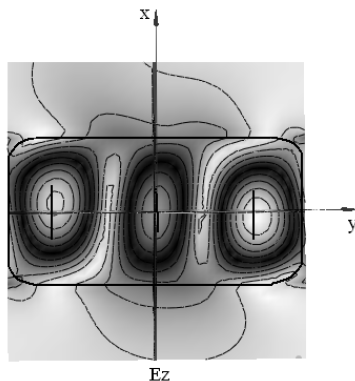


nax. 1.3.63 structuris geometria



nax. 1.3.64 gadasxivebul i simZl avris damokidebul eba  $kd$  parametrze

Semdeg naxazze (nax. 1.3.65) moyvanilia axl o vel is ganawil eba rezonansis SemTxvevaSi ( $kd=1.2075$ ). gabneul i vel is anal izi aCvenebs, rom mas gaaCnia mbrunavi pol arizacia romel ic axl osaa wriul Tan.



nax. 1.3.65 axl o vel is ganawil eba

## daskvna

gamokvl eul ia metal o-diel eqtrikul i struqturabis zogierTi el eqtrodinamikuri Tvisebebi. ganxil ul ia mesris el ementis ramodenime gansxvavebul i forma. moyvanil ia probl emis gadaWris Teoriul i safuZvl ebi. ZiriTad mizans warmoadgenda aseTi struqturabis Seswavl a rezonansul sixSireebze, rodesac isini kompl eqsuri garemos Tvisebebs amJRavneben. kerZod, miRebul ia kiral uri da aseve uaryofiTi gardatexis mqone struqtura. ganxil ul ia axal i saxis el ementi - "kasini" romel sac gaaCnia farTo sixSirul diapazonSi rezonansul i Tvisebebi. ganxil ul ia aseve antenuri amocana, rodesac dacemul i vel is wyaro struqturis SigniT imyofeba. ricxviTi gamoTvl ebis saSual ebiT SerCeul ia struqturis optimal uri parametrebi brtyel i an mimarTul i diagramis misaRebad. gamoTvl ebi Catarebul ia damxmare gamomsxivebl ebis meTodis gamoyenebiT. ricxviTi gamoTvl ebis paral el urad mowmdeboda gamoTvl ebis cdomil eba romel ic ar aRemateboda 2-5%.

unda aRiniSnos, rom am TavSi moyvanil i zogierTi Sedegi statiis saxiT miRebul iqna dasabeWdad imfaqt-faqtorian jurnal Si "Journal of Communications Technology and Electronics" [43].

## Tavi II

brtyel i el eqtromagnituri tal Ris difraqcia usasrul o  
orperiodul meserze Tavisufal garemoSi

## zogadi mimoxil va

es Tavi exeba brtyel i tal Ris difraqcias usasrul o orperiodul meserze [44]. mesris el ementi warmoadgens rezonansul i Tvisebebis, mcire el eqtrul i radiusis da sasrul i sigrZis mqone gamtars. es amocana dResdReobiT metad aqtual uria, radgan kompl eqsuri masal ebis Tvisebebis Seswavl a swored periodul struqturbze difraqciis amocanis amoxsnaze daiyvaneba. praqtikaSi saqme gvaqvs sasrul i zomis mesrebTan, magram Tu am mesris el ementebis raodenoba didia, misi model ireba did kompiuterul resursebTan xdeba dakavSirebul i. amitom ufro martivia ganxil ul i iqnas difraqciis amocana usasrul o periodul struqturaze, romel ic maTematikurad ufro martivad amoixsneba da amave dros vel i axl o areSi faqtiurad ar gansxvavdeba sasrul i zomis mesris SemTxvevisgan.

periodul i struqturbze el eqtromagnituri Tvisebebis gamokvl eva intensiurad daiwyo XX saukunis Suawl ebSi. 1954 wel s ueitma ganxil a sasrul i gamtarebl obis mqone usasrul o sigrZis mavTul ebisgan Semdgari meseri. faqtorizaciis meTodi gamoyenebiT vainSteinis mier ganxil ul i iqna usasrul o sigrZis zol ebisagan Semdgari meseri, roml is periodi zol is siganes udrida. Sestopal ovis mier gamoyenebul i iqna riman - hil bertis ricxviTi meTodi difraqciul i amocanebis amosaxsnel ad.

moyvanil Sromebsi ganxil eboda erTperiodul i mesrebi, anu roml ebic iyvnen periodul ebi mxol od erTi mimarTul ebiT

Tavi II Sedgeba 3 paragrafi sgan:

pirvel i paragrafis dasawyisSi gamoyvanil ia puasonis aj amvis formul a, roml is gamoyeneba amartivebs Semdgom gamoTvl ebs. Semdeg xdeba ZiriTadi amocanis dasma da moyvanil ia misi amoxsnis meTodi. naCvenebia, rom mesris mier gabneul i vel i warmoadgens brtyel i tal Rebis superpozicias.

meore paragrafSi xdeba ucnobi denis amplitudebis gansazRvra mesris el ementebSi. es amocana daiyvaneba wrfiv al gebrul gantol ebaTa sistemaze. moyvanil ia aseve napovni gabneul i vel is gamosaxul eba.

mesame paragrafSi moyvanil ia kompiuterul i model irebis saSual ebiT miRebul i ricxviTi eqsperimentis Sedegebi.

## §2.1 brtyel i tal Ris difraqcia usasrul o orperiodul struqturaze Tavisufal garemoSi

Semdgom gamoTvl ebSi saWiro iqneba usasrul o mwkrivebTan muSaoba da amitom moxerxebul ia maTi gardaqmna cnobil i puasonis aj amvis formul is gamoyenebiT. es gardaqmna gul isxmobs mocemul i mwkrivis Canacvl ebas sxva mwkriviT, romel ic gacil ebiT ufro swrafad ikribeba.

imisaTvis, rom miviRoT aRniSnul i formul a, ganvixil oT Semdegi saxis funqcia:

$$\sum_{n=-\infty}^{+\infty} \delta(x-n),$$

sadac  $\delta$  del ta funqciaa. gasagebia, rom am funqciis mniSvnel oba ar Seicvl eba, Tu mis  $x$  arguments davumatebT raime natural ur ricxvs. es imas niSnavs, rom igi periodul ia da misi periodi erTis tol ia. amis gamo, igi SeiZl eba warmodgenil iqnas furies mwkriviT:

$$\sum_{n=-\infty}^{+\infty} \delta(x-n) = \sum_{\alpha=-\infty}^{+\infty} a_{\alpha} e^{i2\pi\alpha x}.$$

ucnobi  $a_{\alpha}$  furies koeficientebis sapovnel ad gavamravl oT tol obis orive mxare  $e^{-i2\pi px}$ , sadac  $p$  fiqsirebul i natural uri ricxvia da gavaintegroT periodis fargl ebSi:

$$\sum_{n=-\infty}^{+\infty} \int_{-1/2}^{1/2} \delta(x-n) e^{-i2\pi px} dx = \sum_{\alpha=-\infty}^{+\infty} a_{\alpha} \int_{-1/2}^{1/2} e^{i2\pi(\alpha-p)x} dx.$$

marcxena mxareSi gagvaCnia mwkrivis mxol od nul ovani wevri, romel ic udris erTs. yvel a danarCeni wevri nul is tol ia, radgan  $n \notin [-1/2, 1/2]$  rodesac  $n \neq 0$  da Sesabamisad  $\delta(x-n) = 0$ . marj vena mxareSi

$$\int_{-1/2}^{1/2} e^{i2\pi(\alpha-p)x} dx = \frac{\sin(\pi(\alpha-p))}{\pi(\alpha-p)} = \begin{cases} 1, & \alpha = p \\ 0, & \alpha \neq p \end{cases}.$$

maSasadame  $a_p = 1$  da furies yvel a koeficienti erTis tol ia. amitom

$$\sum_{n=-\infty}^{+\infty} \delta(x-n) = \sum_{\alpha=-\infty}^{+\infty} e^{i2\pi\alpha x}.$$

Tu gavamravl ebT bol o tol obis orive mxares raime  $f(x)$  funqciaze da gavaintegrebT interval Si  $(-\infty, +\infty)$ , maSin sabol ood miviRebT

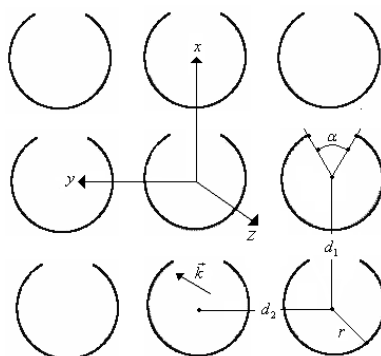
$$\sum_{n=-\infty}^{+\infty} f(n) = \sum_{\alpha=-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x) e^{i2\pi\alpha x} dx.$$

es aris puasonis aj amvis formul a. ormagi mwkrivis SemTxvevaSi SeiZl eba am formul is orjer gamoyeneba, ris Sedegadac miviRebT formul as

$$\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \varphi(m,n) = \sum_{\alpha=-\infty}^{+\infty} \sum_{\beta=-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \varphi(x,y) e^{i2\pi(\alpha x + \beta y)} dx dy.$$

**amocanis dasma.** ganvixil oT  $z=0$  sibrtyeSi usasrul o orperiodul i struqtura, romel ic Sedgeba rezonansul i Tvisebebis mqone gamtar el ementebisagan. naxazze 2.1.1 moyvanil ia meseri, roml is el ementi Ria

rgol s warmoadgens, Tumca qvemoT Camoyal ibebul i Teoria zogadia da is SeiZl eba gamoyenebul iqnas sxva, ufro rTul i formis mqone el ementebis SemTxvevaSi c.



max. 2.1.1. mesris geometria

igul isxmeba, rom el ements gaaCnia mcire  $d_0$  radiusi. mesris periodebi  $OX$  da  $OY$  RerZebis gaswrviv Sesabamisad avRniSnoT rogorc  $d_1$  da  $d_2$ . ganxil ul strukturas ecema droSi harmoniul i brtyel i el eqtromagnituri tal Ra

$$\vec{E}_{inc}(\vec{r}) = \vec{E}_0 e^{i\vec{k}\vec{r}}, \quad \vec{H}_{inc}(\vec{r}) = \vec{H}_0 e^{-i\vec{k}\vec{r}},$$

$$H_0 = E_0 / Z_0, \quad k = 2\pi / \lambda = \omega \sqrt{\epsilon_0 \mu_0}, \quad Z_0 = \sqrt{\mu_0 / \epsilon_0},$$

aq  $\lambda$  tal Ris sigrZea,  $Z_0$  Tavisufal i garemos tal Ruri winaRobaa,  $\vec{k}$  tal Ruri veqtoria,  $\vec{r} \{x, y, z\}$  dakvirvebis wertil is radiusveqtors warmoadgens. drois maxasiaTebel ia  $e^{-i\omega t}$ .

dacemul i tal Ra aRZravs mesris yovel el ementSi ucnobi ampl itudebis mqone denebs roml ebic gadaasxiveben meorad  $\vec{E}(\vec{r})$ ,  $\vec{H}(\vec{r})$  vel s. Cveni amocanaa gavnsazRvroT ucnobi denebi da vipovoT mesris mier gabneul i  $\vec{E}(\vec{r})$ ,  $\vec{H}(\vec{r})$  vel i.

usasrul o periodul obis da brtyel i dacemul i tal Ris gamo mesris el ementebi msgavs pirobebSi imyofebian da yovel maTganze erTi ampl itudis denebi aRiZvreba, roml ebic mxol od fazebiT gansxvavdebian erTmaneTisagan. gansxvavebas am fazebis Soris ar eqneba adgil i marTobul i dacemis SemTxvevaSi. aqedan gamomdinare, gadasxivebul i vel i aseve periodul ia da yovel  $d_1 \times d_2$  areSi gaaCnia erTi da igive saxe.

gadasxivebul i vel is periodul obis gamo, sakmarisia igi Seviswavl oT mxol od erT romel ime  $d_1 \times d_2$  areSi da davakmayofil oT mistvis sasazRvro piroba mxol od am areSi myof el ementze.

mesris yovel i el ementi avRniSnoT rogorc  $l_{mn}$ . aq pirvel i  $m$  indeqsi gviCvenebs el ementis rigis nomers meserSi  $x$  koordinatis gaswrviv, xol o  $n$  indeqsi - svetis nomers  $y$  koordinatis gaswrviv.  $(-\infty < m, n < +\infty)$ . Tu  $\vec{r}_0 \{x_0, y_0, 0\}$  da  $\vec{r}_{mn} \{x_n, y_n, 0\}$  Sesabamisad mesris central uri da  $l_{mn}$  el ementis gaswrviv aRebul i radiusveqtroia, maSin

$$x_n = x_0 + nd_1, \quad y_m = y_0 + md_2.$$

**amocanis amoxsnis meTodi.** mesris yovel i  $l_{mn}$  el ementis mier gadasxivebul i vel i  $\vec{E}_{mn}(\vec{r}), \vec{H}_{mn}(\vec{r})$  - iT aris aRniSnul i. srul i vel i ganisazRvrebam vel ebis j amis saxiT:

$$\vec{E}(\vec{r}) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \vec{E}_{mn}(\vec{r}), \quad \vec{H}(\vec{r}) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \vec{H}_{mn}(\vec{r}).$$

rogorc iqna aRniSnul i, es vel i periodul ia da amitom sakmarisia misi gansazRvra erT romel ime periodis fargl ebSi. moxerxebul ia arCeul iqnas is  $d_1 \times d_2$  periodi, romel ic mesris central ur el ementis Seicavs. ucnobi  $\vec{E}(\vec{r}), \vec{H}(\vec{r})$  vel i unda akmayofil ebdes am el ementis zedapirze Semdeg sasazRvro pirobas:

$$\vec{E}(\vec{r} + d\vec{r}_0) \cdot \vec{l}_0 = -\vec{E}_{inc}(\vec{r} + d\vec{r}_0) \cdot \vec{l}_0, \quad (2.1.1)$$

sadac  $\vec{l}_0$  warmoadgens el ementis zedapiris gaswvri v aRebul tangencial ur veqtors,  $|d\vec{r}_0| = dr_0$  mesris el ementis radiusia. sasazRvro piroba yvel a danarCen el ementze, periodul obis gamo, avtomaturad Sesrul deba.

TviToeul el ementis mier gadasxivebul i vel i veqtorul i da skal arul i potencial iT gamovsaxoT:

$$\vec{E}_{mn}(\vec{r}) = -grad\varphi_{mn}(\vec{r}) + i\omega\vec{A}_{mn}(\vec{r}), \quad \vec{H}_{mn}(\vec{r}) = (1/\mu_0)rot\vec{A}_{mn}(\vec{r}).$$

aqedan gamomdinare

$$\vec{E}(\vec{r}) = -grad\varphi(\vec{r}) + i\omega\vec{A}(\vec{r}), \quad \vec{H}(\vec{r}) = (1/\mu_0)rot\vec{A}(\vec{r}), \quad (2.1.2)$$

sadac

$$\vec{A}(\vec{r}) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \vec{A}_{mn}(\vec{r}), \quad \varphi(\vec{r}) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \varphi_{mn}(\vec{r}) -$$

j amuri potencial ebia.

dakvirvebis wertil Si  $\vec{A}_{mn}(\vec{r})$  da  $\varphi_{mn}(\vec{r})$  potencial ebisTvis davwerT

$$\varphi_{mn}(\vec{r}) = (1/4\pi\epsilon_0) \int_{l_{mn}} \sigma(l_{mn}) e^{ik|\vec{r}-\vec{r}_{mn}|} / |\vec{r}-\vec{r}_{mn}| dl, \quad \vec{A}_{mn}(\vec{r}) = (\mu_0/4\pi) \int_{l_{mn}} I(l_{mn}) e^{ik|\vec{r}-\vec{r}_{mn}|} / |\vec{r}-\vec{r}_{mn}| d\vec{l}.$$

$I(l_{mn})$  da  $\sigma(l_{mn})$  warmoadgenen Sesabamisad  $l_{mn}$  el ementSi aRZrul denis da muxtis ganawil ebas. Tu  $I(l)$  da  $\sigma(l)$  warmoadgenen central uri  $l$  el ementis muxtis da denis ganawil ebas, maSin

$$I(l_{mn}) = I(l) e^{i(nk_x d_1 + mk_y d_2)}, \quad \sigma(l_{mn}) = \sigma(l) e^{i(nk_x d_1 + mk_y d_2)}, \quad \sigma(l) = -(i/\omega) dI(l)/dl.$$

SevitanoT es formul ebi srul i potencial ebis gamosaxul ebebSi, mi vi RebT:

$$\vec{A}(\vec{r}) = (\mu_0/4\pi) \int_l I(l) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} G(\vec{r}, \vec{r}_{mn}) d\vec{l}, \quad (2.1.3)$$

$$\varphi(\vec{r}) = (1/4\pi\epsilon_0) \int_l \sigma(l) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} G(\vec{r}, \vec{r}_{mn}) dl, \quad (2.1.4)$$

sadac

$$G(\vec{r}, \vec{r}_{mn}) = e^{i(nk_x d_1 + mk_y d_2 + k|\vec{r}-\vec{r}_{mn}|)} / |\vec{r}-\vec{r}_{mn}|$$

grinis funqciaa.



vektorul i da skal arul i potencial ebis (2.1.3), (2.1.4) gamosaxul ebebSi figurirebs grinis funqciebis ormagi mwkrivi

$$\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} G(\vec{r}, \vec{r}_{mn}),$$

roml is kreadoba Segvizi ia gacil ebiT gavzardoT Tu gamoviyenebT puasonis miRebul formul as:

$$\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} G(\vec{r}, \vec{r}_{mn}) = \sum_{q=-\infty}^{+\infty} \sum_{p=-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} G(\vec{r}, \vec{r}_{9\tau}) e^{2i\pi(p9+q\tau)} d9d\tau.$$

am gardaqmnis Sedegad mi vi RebT

$$\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} G(\vec{r}, \vec{r}_{mn}) = (2i\pi/d_1 d_2) \sum_{q=-\infty}^{+\infty} \sum_{p=-\infty}^{+\infty} \gamma_{qp}(\vec{r}, \vec{r}_0), \quad (2.1.5)$$

sadac

$$\gamma_{qp}(\vec{r}, \vec{r}_0) = e^{i\vec{k}_{qp}(\vec{r}-\vec{r}_0)} / \sqrt{k^2 - k_{p,x}^2 - k_{q,y}^2},$$

$\vec{k}_{qp} = \vec{k}_{qp} \{k_{p,x}, k_{q,y}, k_{qp,z}\}$ ,  $k_{p,x} = k_x + 2\pi p/d_1$ ,  $k_{q,y} = k_y + 2\pi q/d_2$ ,  $k_{qp,z} = \text{sgn}(z) \sqrt{k^2 - k_{p,x}^2 - k_{q,y}^2}$ .  
rogorc vxedavT, marj vena mxare warmoadgens brtyel i tal Rebis (harmonikebis) j ams. am j amis is komponentebi, romel TaTvis srul deba utol oba

$$k^2 > k_{p,x}^2 + k_{q,y}^2,$$

aramil evad speqtral ur komponentebs warmoadgenen da es - dabal i rigis, komponentebia. SedarebiT maRal i rigis komponentebi, roml iTaTvis srul deba utol oba

$$k^2 < k_{p,x}^2 + k_{q,y}^2,$$

eksponencial urad mil evadia da maTi mniSvel oba mesridan daSorebiT sakmaod swrafad mcirdeba.

SevitanoT (2.1.5) potencial ebis (2.1.3), (2.1.4) gamosaxul ebebSi da movaxdinoT integrireba j amis SigniT. Tu davubrundebiT  $m$ ,  $n$  indeqsebs, maSin dawwerT

$$\vec{A}(\vec{r}) = (i\mu_0/2d_1 d_2) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \int I(l) \gamma_{mn}(\vec{r}, \vec{r}_0) d\vec{l}, \quad (2.1.6)$$

$$\varphi(\vec{r}) = (i/2\varepsilon_0 d_1 d_2) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \int \sigma(l) \gamma_{mn}(\vec{r}, \vec{r}_0) dl, \quad (2.1.7)$$

$$\gamma_{mn}(\vec{r}, \vec{r}_0) = e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_0)} / \sqrt{k^2 - k_{n,x}^2 - k_{m,y}^2}, \quad \vec{k}_{mn} = \vec{k}_{mn} \{k_{n,x}, k_{m,y}, k_{mn,z}\},$$

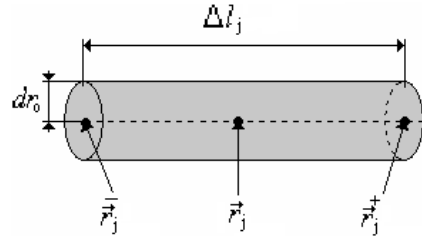
$$k_{n,x} = k_x + 2\pi n/d_1, \quad k_{m,y} = k_y + 2\pi m/d_2, \quad k_{mn,z} = \text{sgn}(z) \sqrt{k^2 - k_{n,x}^2 - k_{m,y}^2}.$$

aq  $m$ ,  $n$  indeqsebi ukve gviCvenebeben harmonikis nomers da ara strukturis el ementis nomers, rogorc Tavidan iTvl eboda. maSasadame Cveni amocanaa vipovoT denis da muxtis ganawil eba central ur el ementSi.

## \$2.2 gabneul i vel is zogadi gamosaxul eba da ucnobi denebis gansazRvra

warmovidginoT central uri el ementi rogorc  $N$  raodenobis segmentebis erTobl ioba. yovel i aseTi segmenti davaxasiaToT Sua da

kidura wertil ebiT, xol o maTi radiusveqtorebi Sesabamisad  $\vec{r}_j^+$ ,  $\vec{r}_j^-$  da  $\vec{r}_j^-$  - T avRni SnoT (max. 2.2.1).



max. 2.2.1. segmentis geometria mesris el ementSi

segmentebis raodenoba aviRoT imdenad didi rom SegveZI os ugul ebel vyoT  $I(l)$  denis cvl il eba yovel maTganis gaswvri. Cven vTvl iT rom yovel  $\Delta l_j$  segmentSi ( $j=1,2,\dots,N$ ) gaedineba ucnobi  $I_j$  ampl itudis deni. es SesaZI oa mxol od im SemTxvevaSi Tu am segmentis bol oebSi imyofeba ori urTierTsapirispino niSnis muxti  $+q_j$  da  $-q_j$  sadac

$$q_j = -(i/\omega)I_j.$$

integral isTvis romelic figurirebs (2.1.6) veqtoreul potencial is gamosaxul ebaSi, davwerT:

$$\int_l I(l)\gamma_{mn}(\vec{r}, \vec{r}_0) d\vec{l} \approx \sum_{j=1}^N I_j \gamma_{mn}(\vec{r}, \vec{r}_j) \Delta \vec{l}_j,$$

sadac  $\vec{r}_j$  warmoadgens  $\Delta l_j$  segmentis Sua wertil is, xol o

$$\gamma_{mn}(\vec{r}, \vec{r}_j) = e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} / \sqrt{k^2 - k_{n,x}^2 - k_{m,y}^2}. \quad (2.2.1)$$

mivaqciOT yuradReba imas, rom yovel i  $\Delta l_j$  segmenti qmnis or skal arul potencial s romelic Seesabameba  $+q_j$  da  $-q_j$  muxtebs. amitom (2.1.7) gamosaxul ebaSi mdebare integral isTvis davwerT:

$$\int_l \sigma(l)\gamma_{mn}(\vec{r}, \vec{r}_0) dl \approx -(i/\omega) \sum_{j=1}^N I_j \Delta [\gamma_{mn}(\vec{r}, \vec{r}_j)],$$

sadac

$$\Delta [\gamma_{mn}(\vec{r}, \vec{r}_j)] = \gamma_{mn}(\vec{r}, \vec{r}_j^+) - \gamma_{mn}(\vec{r}, \vec{r}_j^-).$$

Cven ar vcvl iT  $\Delta [\gamma_{mn}(\vec{r}, \vec{r}_j)]$  sasrul sxvaobas diferencial iT radgan es iqneboda samarTI iani gacil ebiT ufro did  $N$ - sTvis.

Tu SevitanT integral ebis am gamosaxul ebebs (2.1.6) da (2.1.7) formul ebSi, maSin gveqneba

$$\vec{A}(\vec{r}) = (i\mu_0/2d_1d_2) \sum_{j=1}^N I_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \gamma_{mn}(\vec{r}, \vec{r}_j) \Delta \vec{l}_j, \quad (2.2.2)$$

$$\varphi(\vec{r}) = -(1/2\omega\epsilon_0d_1d_2) \sum_{j=1}^N I_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \Delta [\gamma_{mn}(\vec{r}, \vec{r}_j)]. \quad (2.2.3)$$

**gabneul i vel is gamosaxul eba.** gabneul i vel is gamosaxul eba SegviZl ia vipovoT (2.1.2) formul ebis saSual ebiT:

$$\vec{E}(\vec{r}) = -grad\varphi(\vec{r}) + i\omega\vec{A}(\vec{r}), \quad \vec{H}(\vec{r}) = (1/\mu_0)rot\vec{A}(\vec{r}).$$

sai danac mi vi RebT

$$\vec{E}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N I_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \left\{ k^2 \gamma_{mn}(\vec{r}, \vec{r}_j) \Delta \vec{l}_j + i\Delta \left[ \gamma_{mn}(\vec{r}, \vec{r}_j) \right] \vec{k}_{mn,z} \right\}, \quad (2.2.4)$$

$$\vec{H}(\vec{r}) = (1/2d_1 d_2) \sum_{j=1}^N I_j \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} \gamma_{mn}(\vec{r}, \vec{r}_j) (\Delta \vec{l}_j \times \vec{k}_{mn}). \quad (2.2.5)$$

davuSvaT axl a, rom segmentebis  $N$  raodenoba sakmarisad didia imisaTvis, rom SegveZl os sasrul i sxvaoba  $\Delta \left[ \gamma_{mn}(\vec{r}, \vec{r}_j) \right]$  diferencial iT Cavanacvl oT. am SemTxvevaSi (2.2.4) da (2.2.5) formul ebis anal ogiurad, davwerT

$$\vec{E}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N I_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{k}_{mn} \times (\vec{k}_{mn} \times \vec{d}\vec{l}_j)), \quad (2.2.6)$$

$$\vec{H}(\vec{r}) = (1/2d_1 d_2) \sum_{j=1}^N I_j \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{d}\vec{l}_j \times \vec{k}_{mn}). \quad (2.2.7)$$

ganvixil oT am sammagi j amis romel ime erTi wevri (erTerTi harmonika):

$$\vec{E}_{j,mn}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) I_j e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{k}_{mn} \times (\vec{k}_{mn} \times \vec{d}\vec{l}_j)),$$

$$\vec{H}_{j,mn}(\vec{r}) = (1/2d_1 d_2) I_j e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{d}\vec{l}_j \times \vec{k}_{mn}).$$

SeiZl eba naCveneb iqnas, rom am veqtorebis modul ebis Sefardeba sivrcis tal Rur winaRobas udris, rac warmoadgens brtyel i tal Ris erTerT Tvisebas. marTI ac, maTi modul ebi tolia:

$$E_{j,mn}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) I_j e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} k \sqrt{k^2 d\vec{l}^2 - (\vec{k}_{mn} \cdot \vec{d}\vec{l}_j)^2},$$

$$H_{j,mn}(\vec{r}) = (1/2d_1 d_2) I_j e^{i\vec{k}_{mn}(\vec{r}-\vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} \sqrt{k^2 d\vec{l}^2 - (\vec{k}_{mn} \cdot \vec{d}\vec{l}_j)^2},$$

sai danac

$$E_{j,mn}(\vec{r})/H_{j,mn}(\vec{r}) = k/\omega\varepsilon_0 = \sqrt{\mu_0/\varepsilon_0} = Z_0, \quad H_{j,mn}(\vec{r}) = E_{j,mn}(\vec{r})/Z_0.$$

maSasadame, mesris mier gabneul i vel i gamoisaxeba (2.2.6) da (2.2.7) formul ebiT. es vel i warmoadgens mil evadi da aramil evadi brtyel i tal Rebis superpozicias. Cveni amocana dayvanilia imaze rom vipovoT denis  $I_i$  ampl itudebi yovel segmentSi.

**denis ampl itudebis gansazRvra.** denis ucnob ampl itudebs unda gaaCndeT iseTi mniSvel oebi rom srul debodes sasazRvro piroba yovel i segmentis zedapirze:

$$\vec{E}(\vec{r}_g + d\vec{r}_0) \cdot \vec{d}\vec{l}_g = -\vec{E}_{inc}(\vec{r}_g + d\vec{r}_0) \cdot \vec{d}\vec{l}_g, \quad g=1,2,\dots,N. \quad (2.2.8)$$

(2.2.6) da aseve dacemul i vel is formul ebis Tanaxmad

$$\vec{E}(\vec{r}_g + d\vec{r}_0) = (1/2\omega\epsilon_0 d_1 d_2) \sum_{j=1}^N I_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \gamma_{mn}(\vec{r}_g + d\vec{r}_0, \vec{r}_j) (\vec{k}_{mn} \times (\vec{k}_{mn} \times d\vec{l}_j)),$$

$$\vec{E}_{inc}(\vec{r}_g + d\vec{r}_0) = \vec{E}_0 e^{i\vec{k}(\vec{r}_g + d\vec{r}_0)},$$

rac sasazRvro pirobaSi Casmis Sedegad mogvcems ucnobi  $I_j$  ampl itudebis mimarT wrfiv al gebrul gantol ebaTa sistemas

$$\sum_{j=1}^N Z_{jg} I_j = 2\omega\epsilon_0 d_1 d_2 (\vec{E}_0 \cdot d\vec{l}_g), \quad g = 1, 2, \dots, N,$$

sadac

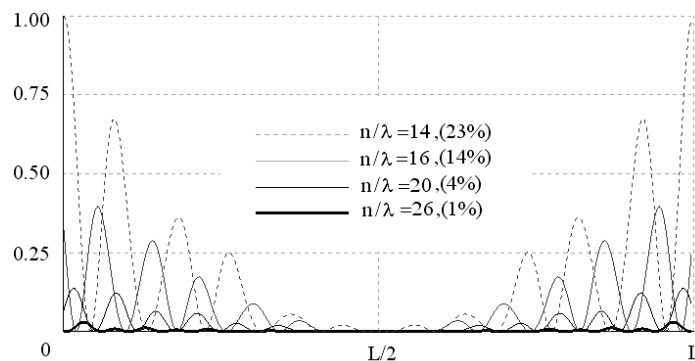
$$Z_{jg} = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} e^{i((\vec{k}_{mn} - \vec{k})(\vec{r}_g + d\vec{r}_0) - \vec{k}_{mn} \vec{r}_j)} (k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{k}_{mn} \times (\vec{k}_{mn} \times d\vec{l}_j)) \cdot d\vec{l}_g.$$

am sistemis amoxsnis Sedegad vpoul obT denebis ampl itudebs da (2.2.6), (2.2.7) formul ebis saSual ebiT gabneul vel s.

### §2.3 ricxviTi eqsperimentebis Sedegebi

**gamoTvl ebis sizustis dadgena.** imisaTvis, rom davrwundeT miRebul i Sedegebis samarTI ianobaSi, mniSvnel ovania SerCeul iqnas mesris el ementebis damxmare parametrebi: mcire segmentebis optimal uri sigrZe da mavTul ebis radiusi dacemul i tal Ris sigrZesTan SedarebiT ( $\Delta l_j/\lambda, dr_0/\lambda$ ). sxvanairad rom vTqvaT, unda davrwundeT, rom Cveni gamoTvl ebi samarTI iania da miRebul i Sedegebis sizuste kontrol irebadia. Tu gaviTval iswinebT, rom ganxil ul i vel ebi akmayofil eben tal Rur gantol ebas da amastanave puasonis gardaqmna aris samarTI iani, maSin amoxsnis sizuste unda iyos damokidebul i sasazRvro pirobebis Sesrul ebaze kol okaciis wertil ebs Soris. am optimal uri parametrebis codna iZl eva saSual ebas maRal i sizustiT gamovikvl ioT usasrul o periodul i struqturebis el eqtrodinamikuri Tvissebebi.

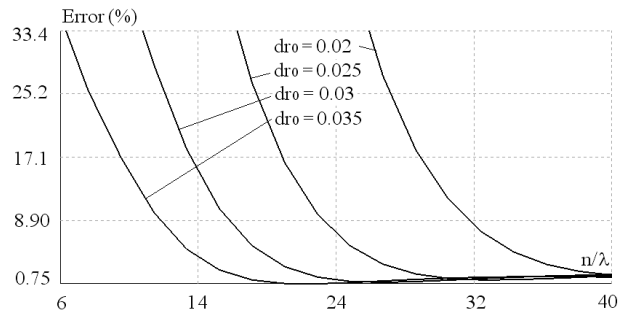
naxazze 2.3.1 moyvanilia sasazRvro pirobis Sesrul ebis damokidebul eba mavTul ze, kol okaciis wertil ebis sxvadasxva raodenobis SemTxvevaSi tal Ris sigrZis gaswrviv.



max. 2.3.1 amoxsnis sizustis Semowmeba

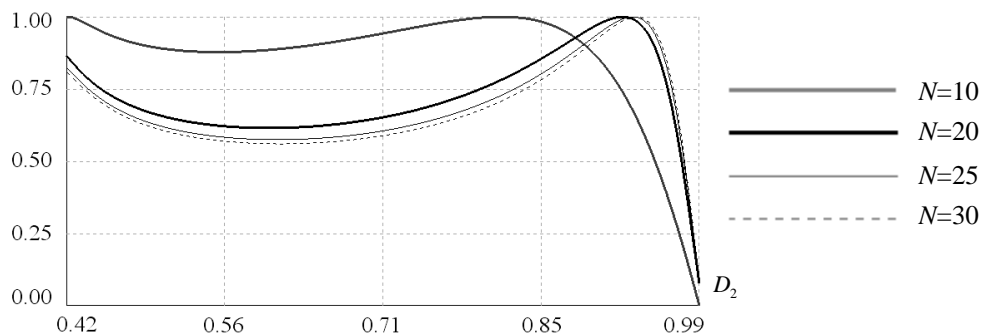
moyvanili gadaxra sasazRvro pirobidan danormirebul ia maqsimumze, romelic miReba, rodesac gagvaCnia tal Ris sigrZeze mosul i mxol od 14

kol okaciis wertil i. rogorc es suraTi gviCvenebs, 20 wertil is SemTxveva, anu rodesac  $n/\lambda=20$ , sakmarisia imisaTvis, rom miviRoT samarTI iani ricxviTi Sedegebi mesris el eqtrodinamikuri Tvisebebis gamosakvl evad. optimal uri damxmare parametrebis Seswavl am gviCvena rom saul eTeso miaxl oveba el eqtrul ad wvril mavTul Tan miiRweva rodesac misi  $dr_0$  raiusi imyofeba  $0.02\lambda$  da  $0.035\lambda$  - s fargl ebSi (nax. 2.3.2).



nax. 2.3.2 cdomil ebis damokidebul eba kol okaciis wertil ebis raodenobaze tal Ris sigrZis gaswrviv, mavTul is sxvadasxva radiusebisaTvis

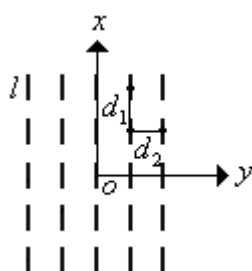
naxazze 2.3.3 moyvanili mrudebi warmoadgenen arekvl is koeficientis damokidebul ebas mesris  $D_2 = d_2/\lambda$  periodze sxvadasxva  $N = n/\lambda$  kol okaciis wertil ebis raodenobisaTvis Ria rgol ebis SemTxvevaSi (nax. 2.1.1). rogorc Cans mrudi mniSvnel ovnad aRar icvl eba  $N=20$  mniSvnel obidan.



nax. 2.3.3 arekvl is R koeficientis damokidebul eba mesris periodze  $D_1=0.5$ ,  $R_0/\lambda=0.2$ , ( $N=10, 20, 25, 30$ ).

Semdeg moyvanili Sedegebi miRebul ia maTi sizustis winaswari SemowmebiT da fizikuri Sinaarsis gaanal izebiT. gamokvl eul i structurebis parametrebi moyvanili uganzomil ebo dayvanil erTeul ebSi ( $D_1 = d_1/\lambda$ ,  $D_2 = d_2/\lambda$  da  $L = l/\lambda$ , sadac  $l$ - mesris el ementis sruli sigrZea). amitom yvel a es Sedegi rCeba samarTI iani farTo sixSirul diapazonSi, sadac SeiZl eba gamoyenebul iqnas maqsvel is kl asikuri Teoria.

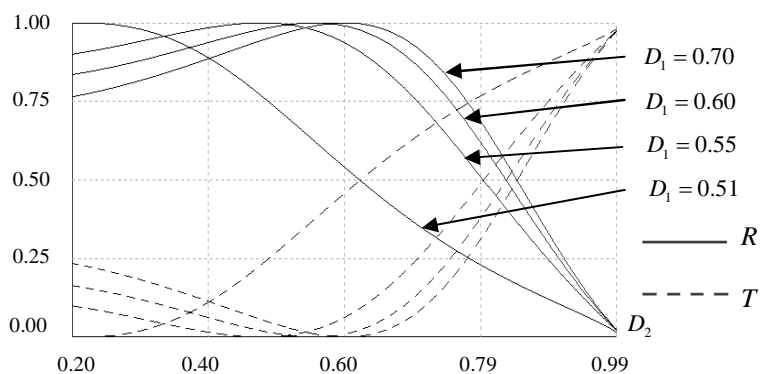
**swor gamtarebisgan Semdgari usasrul o periodul i meseri.** pirvel SemTxvevaSi ganxil ul iqna mesris el ementis umartivesi SemTxveva. el ementi warmoadgens el eqtrul ad mcire  $l$  sigrZis gamtars (nax. 2.3.4).



max. 2.3.4 mesris geometria

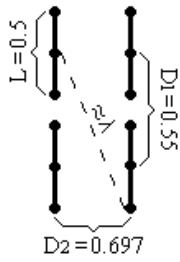
$$\bar{r}_{pq} = \bar{r}_{pq} \left\{ (l/2)\vartheta + pd_1, qd_2, 0 \right\}, \quad -1 \leq \vartheta \leq 1, \quad -\infty < p < +\infty, \quad -\infty < q < +\infty.$$

mesers marTobul ad ecema erTeul ovani ampl itudes mqone brtyel i el eqtromagnituri tal Ra, romel ic vrcel deba OZ RerZis sawinaaRmdego mimarTul ebiT. naxazi 2.3.5 gviCvenebs R arekvl is da T gasvl is koeficientis damokidebul ebas  $D_2 = d_2/\lambda$  periodze sxvadasxva fiqsirebul  $D_1 = d_1/\lambda$  periodis SemTxvevaSi. mesris el ementis sigrZe aris rezonansi ( $L = l/\lambda = 0.5$ ). energiis Senaxvis kanoni moiTxovs, rom arekvl is da gasvl is koeficientebis jami iyos erTis tol i:  $R+T=1$ . rogorc Cans es piroba maRal i sizustiT srul deba, rac aseve miuTitebs miRebul i Sedegis samarTI ianobaze.

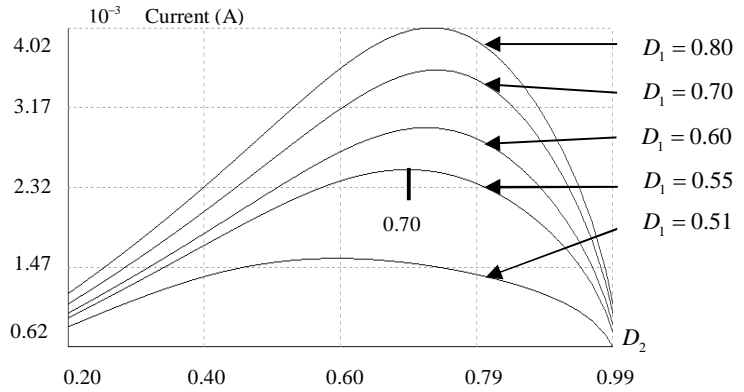


max. 2.3.5 R arekvl is da T gasvl is koeficientebis damokidebul eba mesris periodebze

rodesac  $D_1 = 0.51$  el ementebi TiTqmis exebian erTmaneTs OX RerZis gaswvri. rogorc vxedavT  $R=1$  da  $T=0$  rodesac  $D_1 = 0.51$  da  $D_2 = 0.2$  rac niSnavs imas, rom meseri iqceva rogorc amrekl i zedapiri.  $D_1$  periodis danarCen ganxil ul mniSvnel obebisatvis kvl av arsebobs iseTi  $D_2$  periodi, rodesac meseri sruliad irekl avs dacemul tal Ras. es movl ena Seswavi il iqna siRrmiseul ad, radgan igi dakavSirebul ia rezonansul efeqtebtan. periodebis am mniSvnel obebze, zogierTi manZili mesris el ementebis Soris dacemul i tal Ris  $\lambda$  sifrZis j eradi xdeba, rac rezonansul manZil s Seesabameba (max. 2.3.6).

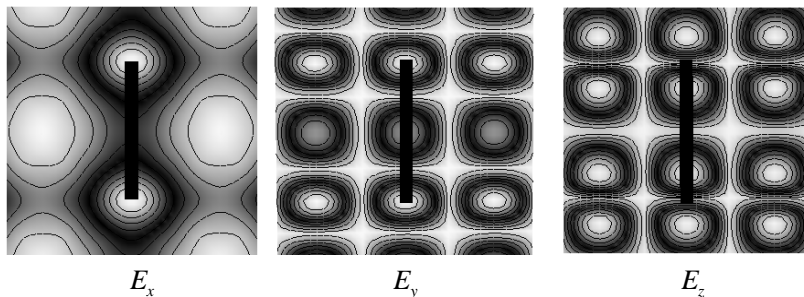


nax. 2.3.6 rezonansul i manzil i el ementebis Soris

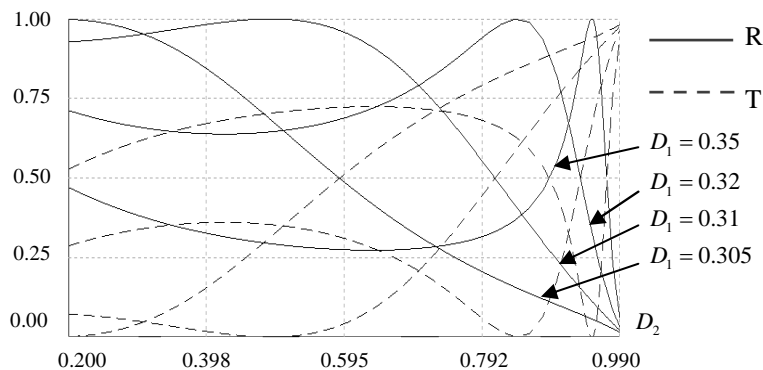


nax. 2.3.7 denis maqsimumis damokidebul eba mesris periodeze. el ementis sigrZea  $0.5\lambda$

2.3.5 naxazis anal ogiurad, interest warmoadgens aseve is, Tu rogoraa damokidebul i el ementSi arZrul i denis maqsimumi mesris periodebze (nax. 2.3.7). yovel i denis mrudis piki naxazze 2.3.7 aseve Seesabameba rezonans magram  $D_2$  periodis rezonansul i mniSvnel obebi naxazebze 2.3.5 da 2.3.7 ar emTxvevian erTmaneTs. arNiSnul i ardamTxveva axsnil iqna Sesabamisi axl o vel is Seswavl is Sedegad. denis rezonansis dros mniSvnel ovdad Zl ierdeba axl o vel i, maSin rodesac Sor zonaSi, sadac gagvaCnia mxol od erTi aramil evadi speqtral uri komponenti, vel i mniSvnel ovdad ar icvl eba.



nax. 2.3.8 axl o vel is komponentebis ganawil eba

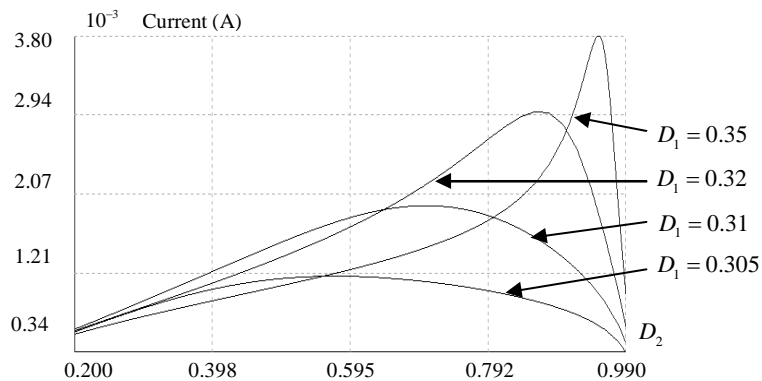


nax. 2.3.9 arekvl is da gasvl is koeficientis damokidebul eba mesris periodeze. el ementis sigrZea  $0.3\lambda$

naxazze 2.3.8 moyvanil ia axl o vel is komponentebis ganawil eba  $z=0$  sibrtysie rterT rezonansis SemTxvevaSi rodesac  $D_1=0.55$ ,  $D_2=0.70$  da meseri iqceva rogorc srul iad amrekl i zedapiri. am suraTze SegviZl ia davinaxoT mdgari tal Ra mesris gaswvriV, romel ic aniWebs mesers amrekl Tvisebebs. cxadia, rom aseTi Tviseba SeiZl eba gamoyenebul iqnas praqtikaSi.

Semdeg ganxil ul iqna SemTxveva rodesac mesris el ementis sigrZe araa rezonansul i ( $L=0.3$ ). naxazze 2.3.9 moyvanil ia arekl is da gasvl is koeficientis damokidebul ebas  $D_2$  periodze sxvadasxva fiqsirebul  $D_1$  periodis SemTxvevaSi. rogorc vxedavT kvl av arsebovs am periodebis iseTi mniSvnel obebi, rodesac zogierTi manZil i mezobel el ementebis Soris xdeba rezonansul i da meseri kvkav iqceva rogorc amrekl i zedapiri.

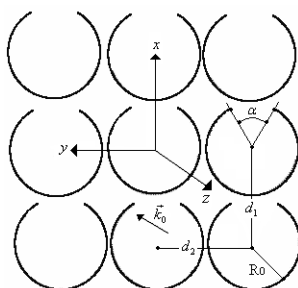
naxazze 2.3.10 moyvanil ia anal ogiuri damokidebul eba el ementebSi aRZrul i denis maqsimumis saTvis. am mrudebis pikebi Seesabamebi an rezonanss.



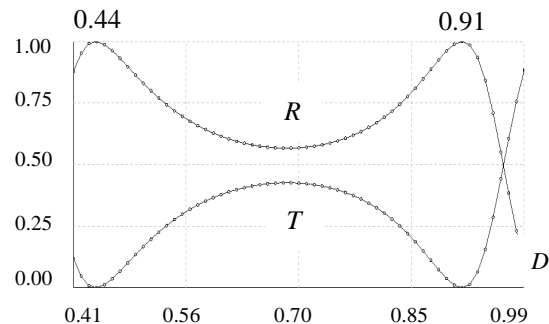
nax. 2.3.10 denis maqsimumis damokidebul eba mesris periodze. el ementis sigrZe  $0.3\lambda$

**Ria gamtari rgol ebisgan Semdgari usasrul o periodul i meseri.**

Semdeg ganxil ul iqna tol i  $D_1=D_2=D$  periodebis mqone usasrul o meseri, rodesac misi el ementi Ria gamtar rgol s warmoadgens (nax. 2.3.11). mesers ecema X pol arizaciis mqone brtyel i tal Ra.



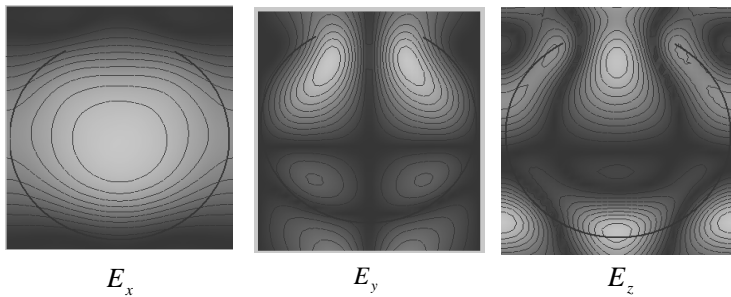
nax. 2.3.11 mesris geometria



nax. 2.3.12 arekl is da gasvl is koeficientis damokidebul eba mesris periodze.  $R_0/\lambda = 0.2$ ,  $N=20$



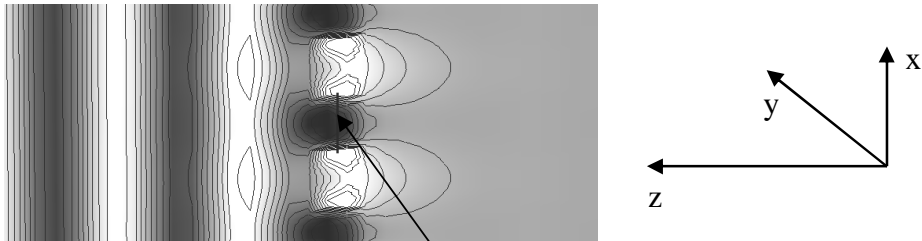
naxazze 2.3.12 moyvanilia  $R$  arekvl is da  $T$  gasvl is koeficientis damokidebul eba mesris  $D$  periodze. rgol is radiusia  $R_0 = 0.2 \lambda$ , Ria seqtoris kuTxea  $30^\circ$ , xol o kol okaciis wertil ebis raodenoba rgol is gaswvriv aris  $N=20$ . rogorc vxedavT, rodesac  $D=0.44$  da  $D=0.91$ , adgil i aqvs dacemul i tal Ris srul arekvl as. aseve, rogorc es iyo swori gamtarebis SemTxvevaSi, es srul i arekvl a Seesabameba ormagi rezonansis SemTxvevas, anu rezonans mesris el ementebis Soris. piroba  $R+T=1$  aseve srul deba.



nax. 2.3.13 axl o vel is komponentebis ganawil eba

naxazze 2.3.13 moyvanilia axl o vel is komponentebis ganawil eba im SemTxvevaSi rodesac  $R_0/\lambda = 0.24$  da mesris periodebi ar emTxveva erTmaneTs ( $D_1 = 0.62$ ,  $D_2 = 0.54$ ). vel is daxatvis sibrtye wanacvl ebul ia mesris sibrtiyidan, romel Sic mas singular aroba gaaCnia.

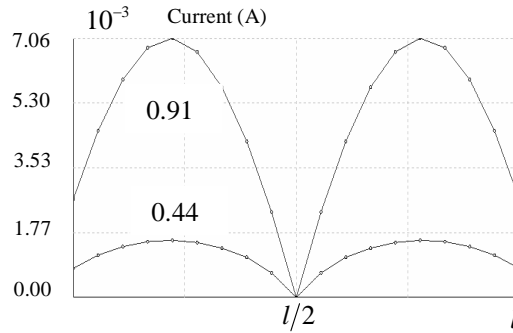
Semdegi kvl av ganixil eba toli periodebis SemTxveva. naxazi 2.3.14 gviCvenebs axl o vel is ganawil ebas mesris perpendikul arul sibrtyeSi rezonansul i periodis SemTxvevaSi  $D=0.91$  (nax. 2.3.12). suraTis marj vena mxareSi Cven vxedavT mdgar tal Ras rac niSnavs dacemul i tal Ris srul arekvl as. marj vena nawil Si dacemul i vel i nawil obriv aRwevs, magram ar vrcel deba masSi, radgan arsebobs fazaTa sxvaoba el eqtrul da magnitur vel s Soris am areSi.



el ementi marTobul sibrtyeSi

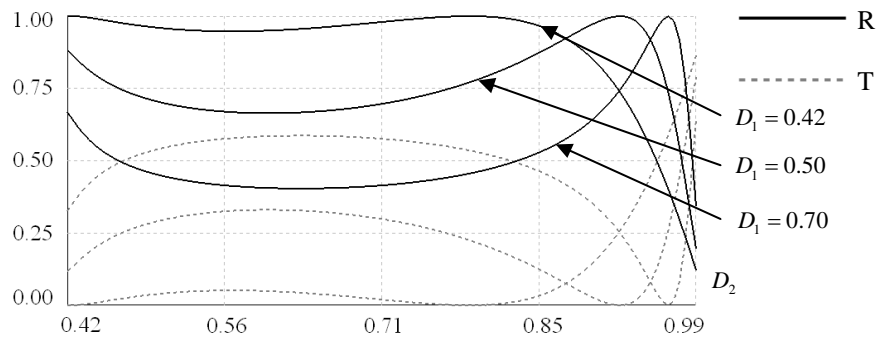
nax. 2.3.14 axl o vel is ganawil eba ormagi rezonansis SemTxvevaSi

Semdegi suraTi (nax. 2.3.15) gviCvenebs el ementi aRZrul i denis ganawil ebas rezonansis dros ( $D=0.44$  da  $D=0.91$ , nax. 2.3.12). rogorc Cans, meore SemTxvevaSi gacil ebit ufro maRal i ampl itudis deni aRizvreb.

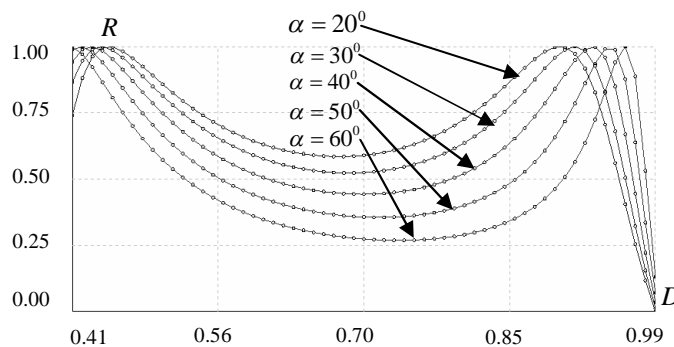


nax. 2.3.15 denis ganawil eba el ementSi

naxazze 2.3.16 moyvanilia arekvl is da gasvl is koeficientebis damokidebul eba  $D_2$  periodze,  $D_1$  periodis sxvadasxa mniSvnel obebisaTvis, rodesac  $R_0=0.2\lambda$ ,  $\alpha=30^\circ$ ,  $N=20$ . interest warmoadgenda aseve arekvl is koeficientis damokidebol eba mesris periodze Ria seqtoris kuTxis sxvadasxa mniSvnel obebisaTvis. miRebul i damokidebul eba moyvanilia naxazze 2.3.17. am suraTis mixedvit Ria seqtoris kuTxis gaSl a iwvevs rezonansis Seviwroebas, rac Seesabameba sixSi reze damokidebul zedapirs.



nax. 2.3.16 arekvl is da gasvl is koeficientis damokidebul eba mesris periodze.  $R_0/\lambda = 0.2$ ,  $N=20$



nax. 2.3.17 arekvl is koeficientis damokidebul eba mesris periodze, sxvadasxa gaSl is kuTxis SemTxvevaSi

## daskvna

am TavSi ganxil eboda brtyel i tal Ris difraqciis amocana organzomil ebian usasrul o periodul meserze. moyvanil ia am amocanis Teoriul i anal izi da aseve ricxviTi eqsperimentebis Sedegebi.

Teoriul nawil Si iqna gamoyenebul i puasonis cnobil i gardaqmna, roml is saSual ebiT gabneul i vel i warmodgenil iqna sivrcul i, mil evadi da aramil evadi speqtral uri komponentebis jamis saxiT. ricxviTi eqsperimentebis Catarebamde Semowmda al goriTmis cdomil eba da dadginda damxmare parametrebis optimal uri mniSvnel obebi, mcire cdomil ebis misaRebad. ganxil ul ia mesris elementis ori gansxvavebul i forma. gamokvl eul iqna mesris gasvl iTi da arekvl iTi Tvisebebi. am TavSi miRebul i Sedegebi gamoqveynebul iqna statiis saxiT Jurnal Si "Journal of Applied Electromagnetism" [46].

## Tavi III

brtyel i el eqtromagnituri tal Ris difraqcia sistemaze  
usasrul o orperiodul i meseri - brtyel i diel eqtriki i fena

## zogadi mimoxil va

am TavSi amoxsnil ia brtyel i el eqtromagnituri tal Ris difraqciis amocana sistemaze brtyel i usasrul o orperiodul i meseri - brtyel i diel eqtrikul i fena [45, 46]. ganixil eba ori gansxvavebul i SemTxveva, rodesac meseri imyofeba diel eqtrikis SigniT da aseve mis maxl obl ad. mesris el ementi kvl av warmoadgens rezonansul i Tvisebebis mqone, brtyel wvril gamtars. zogadad mas SeiZl eba gaaCndes rTul i forma. moyvanil ia sami meTodi dasmul i amocanis amosaxsnel ad.

difraqciis amocana diel eqtikSi moTavsebul periodul meserze dResdReobiT metad aqtual ur probl emas warmoadgens radgan aseTi saxis struqturebi, erTianobaSi garkveul sixSireebze, saintereso rezonansul Tvisebebs amJRavneben. es aixsneba imiT, rom rezonansul i el ementebis gaerTianeba sistemaSi aZl ierebs maT Soris urTierTqmedebas, rac iwvevs denis amplitudis mkveTr gazrdas yovel el ementSi. aRniSnul i urTierTqmedeba damokidebul ia agreTve manZil ze el ementebis Soris da es manZil i aseve SeiZl eba iyos rezonansul i. amasTanave, aRniSnul i rezonansul i efeqtebi damokidebul ia agreTve mesris el ementis geometriul formaze. rodesac sistema moTavsebul ia naxebrad gamWvirval e diel eqtrikul i zedapiris SigniT, cxadia, moizebneba srul i sistemis iseTi parametrebi, rodesac ganxil ul i efeqtebi mkveTrad izrdeba da swored aseTi SemTxvevebis Seswavl a warmoadgens metad saintereso amocanas.

mesame Tavi Sedgeba sam paragrafisgan:

pirvel paragrafSi ganixil eba SemTxveva, rodesac meseri diel eqtrikis SigniT imyofeba. am amocanis amosaxsnel ad gamoyenebul ia damxmare gamomsxivebl ebis meTodi. amisaTvis napovni qna periodul i grinis funqcia, romel ic iyo gamoyenebul i rogorc damxmare gamomsxivebl is vel i. es niSnavs am meTodis ganviTarebas da morgebas aseTi saxis amocanebze.

meore paragrafSi ganixil eba SemTxveva, rodesac meseri imyofeba fenis maxl obl ad. damxmare gamomsxivebl ebis meTodTan erTad moyvanil ia aseve am amocanis mkacri amoxsnis ori meTodi.

mesame paragrafSi moyvanil ia miRebul i ricxviti eqsperimentebis Sedegebi.

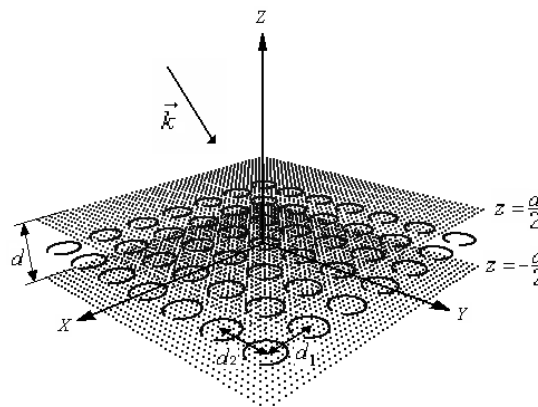
### §3.1 brtyel i tal Ris difraqcia diel eqtrikul fenaSi moTavsebul usasrul o orperiodul meserze

**amocanis dasma.** ganvixil oT sasrul i  $d$  sisqis mqone usasrul o diel eqtrikul i fena Tavisufal garemoSi, romelic  $XOY$  sibrtiyis paral el uradaa orientirebul i. fena SemosazRvrul ia  $z=d/2$ ,  $z=-d/2$  zedapirebiT da daxasiaTebul ia  $\varepsilon$  diel eqtrikul i da  $\mu$  magnituri SeRwevadobebiT. am fenis SigniT,  $z=0$  sibrtyeSi imyofeba organzomil ebiani usasrul o,  $d_1$  da  $d_2$  periodebis mqone meseri, roml is el ementia, brtyel i mcire radiusis da rezonansul i Tvisebebis mqone gamtari (max. 3.1.1).

aRniSnul struqturas  $z > d/2$  naxevarsivrcidan ecema cnobil i droSi harmoniul i brtyel i el eqtromagnituri tal Ra, roml is mimarTul eba  $\vec{k}$  tal Ruri veqtoriT ganisazRvreba:

$$\vec{E}_{inc}(\vec{r}) = \vec{E}_0 e^{i\vec{k}\vec{r}}, \quad \vec{H}_{inc}(\vec{r}) = \vec{H}_0 e^{i\vec{k}\vec{r}}, \quad H_0 = \sqrt{\varepsilon_0/\mu_0} E_0. \quad (3.1.1)$$

aq  $\vec{r} \{x, y, z\}$  dakvirvebis wertil is radiusveqtoria. drois maxasiaTebel ia  $e^{-i\omega t}$ . saZiebel ia gasul i vel i, arekvl il i vel i da aseve vel i struqturis SigniT.



max. 3.1.1 meseri diel eqtrikSi

Cveni amocanaa, vipovoT difraqirebul i vel i struqturis zeviT, mis qveviT da aseve mis SigniT.

**Ddamxmare gamomsxivebl ebis meTodis gamoyeneba:** ganxil ul i amocanis Teoriul ad gadawyvetisaTvis, moxerxebul ia gamoyenebul iqnas damxmare gamomsxivebl ebis meTodi. rogorc cnobil ia, am meTodis gamoyenebis dros erTerT principul sakiTxs warmoadgens damxmare gamomsxivebl ebis SerCeva, roml is maTematikuri gamosaxul eba unda akmayofil ebdes saTanado amocanis diferencial ur gantol ebas da unda warmoadgendes am gantol ebis grinis funqcias.

usasrul o periodul i mesris SemTxvevaSi, xdeba saWiro periodul i struqturis grinis funqciis gansazRvra. wina TavSi Cvens mier miRebul iqna usasrul o periodul i mesris mier gamomsxivebul i vel is gamosaxul eba. es gamosaxul eba iqna miRebul i mesris el ementis dayofis gziT didi raodenobis mcire segmentebad. gasagebia, rom yovel konkretul segments

mesris romel ime el ementSi, Seesabameba aseTive segmentebi mis mezobel el ementebSi da aseTi msgavsi el ementebis erTobl ioba qmian imave periodebis mqone usasrul o mesers. zustad aseTi segmentebisgan Semdgari mesris mier gamosxivebul vel s unda vuwodoT periodul i grinis funqcia. maSasadame, damxmare gamomsxivebl ebis meTodis gamoyenebis dros, unda davuSvaT, rom wertil ovani damxmare wyaro asxivebs vel s, romel ic gamoi saxeba Semdegnai rad:

$$\vec{G}_E(\vec{r}, \vec{r}_\alpha) = (1/2\omega\varepsilon_0\varepsilon d_1 d_2) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} e^{ik_{\alpha,mm}(\vec{r}-\vec{r}_\alpha)} (\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{k}_{\alpha,mm} \times (\vec{k}_{\alpha,mm} \times \vec{p}_\alpha)), \quad (3.1.2)$$

$$\vec{G}_H(\vec{r}, \vec{r}_\alpha) = (1/2d_1 d_2) \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} e^{ik_{\alpha,mm}(\vec{r}-\vec{r}_\alpha)} (\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{p}_\alpha \times \vec{k}_{\alpha,mm}), \quad (3.1.3)$$

$$\vec{k}_{\alpha,mm} = \vec{k}_{\alpha,mm} \left\{ k_{n,x}, k_{m,y}, \text{sgn}(z - z_\alpha) \sqrt{\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2} \right\}, \quad k_{n,x} = k_x + 2\pi n/d_1, \quad k_{m,y} = k_y + 2\pi m/d_2.$$

aq  $\vec{r}_\alpha \{x_\alpha, y_\alpha, z_\alpha\}$  am damxmare gamomsxivebl is radiusveqtoria,  $\vec{p}_\alpha$  erTeul ovani veqtoria, romel ic gansazRvraS am wyaros orientacias. aqve unda aRiniSnos, rom ganxil ul grinis funqcias gaaCnia singul aroba (ormagi mwkrivi ganSI adia) sibrtyeSi  $z = z_\alpha$ , radgan fizikurad, es aris is sibrtye, saidanac vrcel debian brtyel i tal Rebi  $z > z_\alpha$  da  $z < z_\alpha$  naxevarsi vrceebSi.

brtyel i dacemul i tal Ris da mesris usasrul obis gamo, ucnobi gabneul i vel i yovel areSi aseve periodul ia da yovel i periodis fargl ebSi erTi da igive amplitudis real uri nawil i gaaCnia. amitom Cvens mier ganxil ul iqneba mxol od sivrcis is nawil i, roml is wertil ebisaTvisac srul deba Semdegi piroba:  $(x, y) \in (d_1 \times d_2)$ .

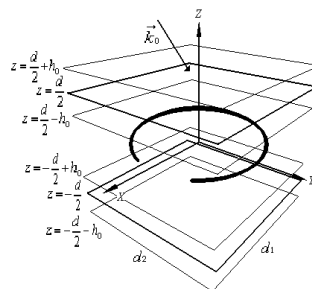
amocanis amoxsnis dros Cven dagvWirdeba aseve im vel is gamosaxul eba, romel sac asxivebs meseri diel eqtrikis gareSe. es gamosaxul eba ukve iqna Cvens mier gamoyvanil i da mas axl a pirdapir movi vyanT:

$$\vec{E}(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_E(\vec{r}, \vec{r}_j), \quad \vec{H}(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_H(\vec{r}, \vec{r}_j). \quad (3.1.4)$$

axl a gadavideT uSual od damxmare gamomsxivebl ebis meTodis gamoyenebaze. avagoT diel eqtrikis SigniT da gareT, zeda da qveda zedapiridan mcire  $h_0$  manZil iT daSorebul i oTxi damxmare zedapiri:

$$z = d/2 - h_0, \quad z = -d/2 + h_0, \quad z = d/2 + h_0, \quad z = -d/2 - h_0.$$

rogorc Cans, pirvel i da meore damxmare zedapirebi struqturis SigniT imyofebian, xol o danarCeni ori - mis gareT.



max. 3.1.2 ganxil ul i are  $(x, y) \in (d_1 \times d_2)$

yvel a damxmare zedapirze vaTavsebT zemoT aRniSnul damxmare gamomsxivebl ebs. damxmare gamomsxivebl ebiT Sida zedapirebze aRiwereba vel i struqturis gareT, xol o gare damxmare zedapirebze mdebare gamomsxivebl ebiT - vel i struqturis SigniT. gasagebia, rom aq, gare damxmare wyaroebis vel is garda arsebobs aseve mesris mier gabneul i vel i. gamosakvl evi periodul i struqtura samganzomil ebiana da amitom yovel i damxmare gamomsxivebel i unda Sedgebodes or urTierTmarTobul el ementarul wyarosgan. es imas niSnavs, rom maTi orientacia unda ganisazRvrebodes Sesabamisad  $\bar{x}$  da  $\bar{y}$  bazisuri veqtorebiT. amastanave, orive el ementarul wyaros damxmare gamomsxivebel Si unda gaaCndes sakuTari ucnobi ampl itudebi.

naTqvamis gaTval iswinebiT davveroT zogadad difraqciis Sedegad warmoqnil i vel ebi.

are (I) - struqturis zeviT. aq gagvaCnia vel i, romel ic aRiwereba

Sida  $z = \frac{d}{2} - h_0$  damxmare zedapiriT da aseve dacemul i vel i:

$$\vec{E}_{inc}(\vec{r}) + \vec{E}_e(\vec{r}) = \vec{E}_0 e^{ik\vec{r}} + \sum_{\alpha=1}^Q \sum_{\alpha'=1}^P \left( A_{\alpha\alpha'} \vec{G}_E^x(\vec{r}, \vec{r}_{\alpha\alpha'}) + B_{\alpha\alpha'} \vec{G}_E^y(\vec{r}, \vec{r}_{\alpha\alpha'}) \right), \quad (3.1.5)$$

$$\vec{H}_{inc}(\vec{r}) + \vec{H}_e(\vec{r}) = \vec{H}_0 e^{ik\vec{r}} + \sum_{\alpha=1}^Q \sum_{\alpha'=1}^P \left( A_{\alpha\alpha'} \vec{G}_H^x(\vec{r}, \vec{r}_{\alpha\alpha'}) + B_{\alpha\alpha'} \vec{G}_H^y(\vec{r}, \vec{r}_{\alpha\alpha'}) \right), \quad (3.1.6)$$

$$z_{\alpha\alpha'} = d/2 - h_0, \quad z \in [d/2, +\infty), \quad \text{sgn}(z - z_{\alpha\alpha'}) = 1.$$

aq  $Q \times P$  damxmare gamomsxivebl ebis raodenobaa erT damxmare zedapirze,  $\alpha\alpha'$  indeqsebs warmoadgenen, romel nic gviCvenebs am wyaros nomers,  $A_{\alpha\alpha'}$  da  $B_{\alpha\alpha'}$  misi ucnobi ampl itudebia,  $x$  da  $y$  indeqsi gviCvenebs romel ortis gaswvriava orientirebul i misi el ementarul i wyaro.

are (II) - struqturis SigniT. aq gagvaCnia  $z = d/2 + h_0$  da  $z = -d/2 - h_0$  damxmare zedapirebis mier Seqmnil i vel i da aseve mesris mier gabneul i vel i:

$$\vec{E}(\vec{r}) + \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_E(\vec{r}, \vec{r}_j) + \sum_{\beta=1}^Q \sum_{\beta'=1}^P \left( C_{\beta\beta'} \vec{G}_E^x(\vec{r}, \vec{r}_{\beta\beta'}) + D_{\beta\beta'} \vec{G}_E^y(\vec{r}, \vec{r}_{\beta\beta'}) \right) + \sum_{\gamma=1}^Q \sum_{\gamma'=1}^P \left( F_{\gamma\gamma'} \vec{G}_E^x(\vec{r}, \vec{r}_{\gamma\gamma'}) + L_{\gamma\gamma'} \vec{G}_E^y(\vec{r}, \vec{r}_{\gamma\gamma'}) \right), \quad (3.1.7)$$

$$\vec{H}(\vec{r}) + \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_H(\vec{r}, \vec{r}_j) + \sum_{\beta=1}^Q \sum_{\beta'=1}^P \left( C_{\beta\beta'} \vec{G}_H^x(\vec{r}, \vec{r}_{\beta\beta'}) + D_{\beta\beta'} \vec{G}_H^y(\vec{r}, \vec{r}_{\beta\beta'}) \right) + \sum_{\gamma=1}^Q \sum_{\gamma'=1}^P \left( F_{\gamma\gamma'} \vec{G}_H^x(\vec{r}, \vec{r}_{\gamma\gamma'}) + L_{\gamma\gamma'} \vec{G}_H^y(\vec{r}, \vec{r}_{\gamma\gamma'}) \right), \quad (3.1.8)$$

$$z_{\beta\beta'} = d/2 + h_0, \quad z_{\gamma\gamma'} = -d/2 - h_0, \quad z \in [-d/2, d/2], \quad \text{sgn}(z - z_{\beta\beta'}) = -1, \quad \text{sgn}(z - z_{\gamma\gamma'}) = 1.$$

are (III) - struqturis qveviT. aq gagvaCnia mxol od gasul i vel i, romel ic  $z = -d/2 + h_0$  zedapiriT aRiwereba:

$$\vec{E}_s(\vec{r}) = \sum_{\delta=1}^Q \sum_{\delta'=1}^P \left( K_{\delta\delta'} \vec{G}_E^x(\vec{r}, \vec{r}_{\delta\delta'}) + R_{\delta\delta'} \vec{G}_E^y(\vec{r}, \vec{r}_{\delta\delta'}) \right), \quad (3.1.9)$$



$$\vec{H}_s(\vec{r}) = \sum_{\delta=1}^Q \sum_{\delta'=1}^P \left( K_{\delta\delta'} \vec{G}_H^x(\vec{r}, \vec{r}_{\delta\delta'}) + R_{\delta\delta'} \vec{G}_H^y(\vec{r}, \vec{r}_{\delta\delta'}) \right), \quad (3.1.10)$$

$$z_{\delta\delta'} = -d/2 + h_0, \quad z \in (-\infty, -d/2], \quad \text{sgn}(z - z_{\delta\delta'}) = -1.$$

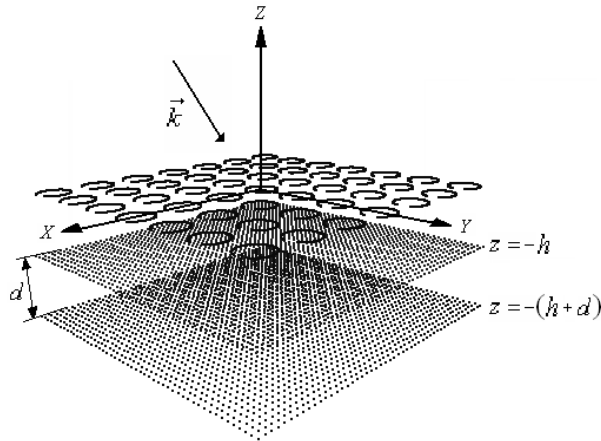
**ucnobi ampl itudebis gansazRvra.** Cveni amocana dayvanil ia imaze rom vipovoT denis ucnobi  $I_j$  ampl itudebi ( $j=1,2,\dots,N$ ) da damxmare gamomsxivebl ebis ampl itudebi  $A_{\alpha\alpha'}, B_{\alpha\alpha'}, C_{\beta\beta'}, D_{\beta\beta'}, F_{\gamma\gamma'}, L_{\gamma\gamma'}, K_{\delta\delta'}, P_{\delta\delta'}$ , sadac ( $\alpha, \beta, \gamma, \delta = 1, 2, \dots, Q, \alpha', \beta', \gamma', \delta' = 1, 2, \dots, P$ ). sul gagvaCnia  $8Q \times P + N$  ucnobi da isini sasazRvro pirobedidan unda vipovoT. diel eqtrikis zedapirze moviTxovT sasazRvro pirobis Sesrul ebas  $Q \times P$ - cal gansxvavebul wertil Si. aseve viTxovT sasazRvro pirobis Sesrul ebas mesris el ementis  $N$  segmentze:

$$\left\{ \begin{array}{l} \left( \vec{E}_{inc}(\vec{r}_{\varphi\varphi'}) + \vec{E}_e(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{x} = \left( \vec{E}(\vec{r}_{\varphi\varphi'}) + \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{x} \\ \left( \vec{E}_{inc}(\vec{r}_{\varphi\varphi'}) + \vec{E}_e(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{y} = \left( \vec{E}(\vec{r}_{\varphi\varphi'}) + \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{y} \\ \left( \vec{E}(\vec{r}_{\varphi\varphi'}) + \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=-d/2} \cdot \vec{x} = \vec{E}_s(\vec{r}_{\varphi\varphi'})_{z_{\varphi\varphi'}=-d/2} \cdot \vec{x} \\ \left( \vec{E}(\vec{r}_{\varphi\varphi'}) + \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=-d/2} \cdot \vec{y} = \vec{E}_s(\vec{r}_{\varphi\varphi'})_{z_{\varphi\varphi'}=-d/2} \cdot \vec{y} \\ \left( \vec{H}_{inc}(\vec{r}_{\varphi\varphi'}) + \vec{H}_e(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{x} = \left( \vec{H}(\vec{r}_{\varphi\varphi'}) + \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{x} \\ \left( \vec{H}_{inc}(\vec{r}_{\varphi\varphi'}) + \vec{H}_e(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{y} = \left( \vec{H}(\vec{r}_{\varphi\varphi'}) + \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=d/2} \cdot \vec{y} \\ \left( \vec{H}(\vec{r}_{\varphi\varphi'}) + \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=-d/2} \cdot \vec{x} = \vec{H}_s(\vec{r}_{\varphi\varphi'})_{z_{\varphi\varphi'}=-d/2} \cdot \vec{x} \\ \left( \vec{H}(\vec{r}_{\varphi\varphi'}) + \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right)_{z_{\varphi\varphi'}=-d/2} \cdot \vec{y} = \vec{H}_s(\vec{r}_{\varphi\varphi'})_{z_{\varphi\varphi'}=-d/2} \cdot \vec{y} \\ \left( \vec{E}(\vec{r}_\sigma) + \vec{E}_f(\vec{r}_\sigma) + \vec{E}_g(\vec{r}_\sigma) \right) \cdot d\vec{l}_\sigma = 0, \end{array} \right.$$

sadac  $\varphi = 1, 2, \dots, Q, \varphi' = 1, 2, \dots, P, \sigma = 1, 2, \dots, N$ . am sistemis amoxsna kompiuterul i model irebiT xdeba. amis Semdeg SegviZl ia vipovoT difraqciis Sedegad miRebul i vel i sivrcis nebismier wertil Si (3.1.5) – (3.1.10) formul ebis saSual ebiT.

### **§3.2 brtyel i tal Ris difraqcia diel eqtrikul i fenis maxl obl ad moTavsebul usasrul o orperiodul meserze**

**amocanis dasma.** ganvixil oT  $d$  sisqis da  $\varepsilon, \mu$  SeRwevadobebis mqone brtyel i diel eqtrikul i fena. periodul i meseri, roml is periodebia  $d_1$  da  $d_2$  imyofeba fenisgan  $h$  simaRl eze da misi yvel a el ementi erT sibrtyeSi imyofeba (max. 3.2.1).



nax. 3.2.1 sistemis geometria

mesers ecema cnobil i, droSi harmoniul i brtyel i el eqtromagnituri tal Ra

$$\vec{E}_{inc}(\vec{r}) = \vec{E}_0 e^{i\vec{k}\vec{r}}, \quad \vec{H}_{inc}(\vec{r}) = \vec{H}_0 e^{i\vec{k}\vec{r}}, \quad (3.2.1)$$

sadac  $\vec{r} = \vec{r}\{x, y, z\}$  dakvirvebis wertil is radiusveqtoria,  $\vec{k} = \vec{k}\{k_x, k_y, k_z\}$  tal Ruri veqtoria,  $k = \omega\sqrt{\epsilon_0\mu_0}$ . droze damokidebul eba gamoisaxeba rogorc  $e^{-i\omega t}$ . Cveni amocanaa vipovoT difragirebul i vel ebi Semdeg areebSi: (I)-mesris zeviT, (II)-mesersa da diel eqtrikul i fenis Soris, (III)-diel eqtrikul i fenis SigniT, (IV)-diel eqtrikul i fenis qveviT.

radgan, meseri usasrul o periodul ia da dacemul i tal Ra aris brtyel i, aqedan gamomdinare difragirebul vel ebs yvel a areSi sivrcul i periodul oba unda gaaCndeT da amitom Cvens mier ganxil ul iqneba mxol od erTi aseTi periodi, anu sivrcis is nawil i, roml is wertil ebis koordinatebisaTvis srul deba pirobebi

$$x \in [-d_1/2, d_1/2], \quad y \in [-d_2/2, d_2/2], \quad z \in (-\infty, +\infty).$$

gasagebia, rom sivrcis es nawil i mxol od mesris central ur (nul ovan) el ements Seicavs.

SemoviRoT sakoordinato sistema ise, rom meseri imyofebodes XOY sibrtyeSi, xol o diel eqtrikul i fenis zedapirebs warmoadgendnen  $z = -h$  da  $z = -(h+d)$  sibrtyeebi. mesris nul ovani el ementis el eqtrul ad mcire radiusi avRniSnoT rogorc  $dr_0$ , xol o am el ementis central uri wiris gantol eba parametrul i saxiT SemoviRoT:

$$x_0 = x_0(t), \quad y_0 = y_0(t), \quad z_0 = z_0(t) \equiv 0, \quad t \in [t_1, t_2].$$

pirvel areSi gagvaCnia dacemul i vel i da aseve mesrisgan zeviT mimaval i vel ebi:

$$(I): \quad \vec{E}_{inc}(\vec{r}) + \vec{E}_1(\vec{r}), \quad \vec{H}_{inc}(\vec{r}) + \vec{H}_1(\vec{r}), \quad z > dr_0. \quad (3.2.2)$$

anal ogiurad, meore areSi gagvaCnia mesrisgan qveviT mimaval i vel ebi da aseve  $z = -h$  zedapiridan arekvl il i vel ebi:

$$(II): \quad \vec{E}_2(\vec{r}) + \vec{E}_e(\vec{r}), \quad \vec{H}_2(\vec{r}) + \vec{H}_e(\vec{r}), \quad -h < z < -dr_0. \quad (3.2.3)$$

mesame areSi gagvaČnia  $z=-h$  zedapiridan gardatexil i vel ebi da aseve  $z=-(h+d)$  zedapiridan zeviT arekvl il i vel ebi:

$$(III): \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}), \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}), -(h+d) < z < -h. \quad (3.2.4)$$

meoTxe areSi gagvaČnia mxol od  $z=-(h+d)$  zedapiridan qveviT mimaval i (gasul i) vel ebi:

$$(IV): \vec{E}_s(\vec{r}), \vec{H}_s(\vec{r}), z < -(h+d). \quad (3.2.5)$$

Cven ar ganvixil avT Txel fenas  $-dr_0 \leq z \leq dr_0$  romel Sic mesridan wamosul vel ebs singul aroba gaaČniaT.

aRniSnul i vel ebi unda akmayofil ebdnen sasazRvro pirobebs diel eqtrikul i fenis orive zedapirze da aseve mesris el ementebis gaswvri. am pirobebis raodenoba udris cxras. erTi piroba iwereba mesris el ementis zedapirze, ris gamoc mas l okal uri xasiaTi gaaČnia da igi mdgomareobs jamuri el eqtrul i vel is tangencial uri mdgenel is nul Tan tol obaSi:

$$\left( \vec{E}_{inc}(\vec{r}_\sigma) + \vec{E}_1(\vec{r}_\sigma) + \vec{E}_e(\vec{r}_\sigma) \right) \cdot \vec{r} = 0. \quad (3.2.6)$$

aq  $\vec{r}_\sigma$  aris el ementis zedapirze aRebul i wertil is radiusveqtori, xol o  $\vec{r}$  warmoadgens am wertil Si gavl ebul tangencial s. radgan mesris el ementi wrilia, Cven ar ganvixil avT im tangencial s romel sac radial uri mimarTul eba gaaČnia.

danarČeni rva piroba unda exebodes diel eqtrikul i fenis zedapirebs, romel ic araa l okal uri da zedapiris yvel a wertil Si unda srul debodes. gagvaČnia ori zedapiri da Sesabamisad yovel maTganze oTxi sasazRvro pirobaa dasaweri. am oTxi pirobidan ori unda daiweros el eqtrul i vel istvis, xol o danarČeni ori - magnituristvis (radgan diel eqtrikis zedapirs ori wrfivad damoukidebel i tangencial i gaaČnia). rogorc viciT, diel eqtrikis zedapirze moiTxoveba daZabul obis veqtoris tangencial uri mdgenel is uwyvetobis piroba. maSasadame

$$\left\{ \begin{array}{l} \left( \vec{E}_2(\vec{r}) + \vec{E}_e(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{x} = \left( \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{x} \\ \left( \vec{H}_2(\vec{r}) + \vec{H}_e(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{x} = \left( \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{x} \\ \left( \vec{E}_2(\vec{r}) + \vec{E}_e(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{y} = \left( \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{y} \\ \left( \vec{H}_2(\vec{r}) + \vec{H}_e(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{y} = \left( \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) \right) \Big|_{z=-h} \cdot \vec{y} \\ \left( \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) \right) \Big|_{z=-(h+d)} \cdot \vec{x} = \vec{E}_s(\vec{r}) \Big|_{z=-(h+d)} \cdot \vec{x} \\ \left( \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) \right) \Big|_{z=-(h+d)} \cdot \vec{x} = \vec{H}_s(\vec{r}) \Big|_{z=-(h+d)} \cdot \vec{x} \\ \left( \vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) \right) \Big|_{z=-(h+d)} \cdot \vec{y} = \vec{E}_s(\vec{r}) \Big|_{z=-(h+d)} \cdot \vec{y} \\ \left( \vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) \right) \Big|_{z=-(h+d)} \cdot \vec{y} = \vec{H}_s(\vec{r}) \Big|_{z=-(h+d)} \cdot \vec{y} \end{array} \right. \quad (3.2.7)$$

**amocanis amoxsna pirvel i meTodiT.** dasmul i amocanis amoxsnis dros Cven dagvWirdeba im vel is gamosaxul eba, romel sac meseri asxivebs diel eqtrikul o fenis gareSe. es gamosaxul eba warmoadgens brtyel i mil evadi da aramil evadi tal Rebis j ams. igi iqna napovni naSromis wina TavSi da amitom mas moviyvanT gamoyvanis gareSe. aq mxol od gavixsenebT, rom igi miRebul ia mesris el elementis warmodgeniT rogorc didi  $N$  raodenobis mcire  $dl$  sigrzis mqone segmentebis erTobl ioba ( $|\vec{dl}_j| = dl$ ,  $j=1,2,\dots,N$ ),  $\vec{r}_j$  warmoadgens  $j$  segmentis radiusveqtors,  $A_j$  ucnobi koeficientebia da yovel i maTgani, fizikurad warmoadgens Sesabamis segmentSi arZrul dens.

Cven cal -cal ke ganvixil avT zeviT da qveviT mimalval vel ebs. amitom:

$$\vec{E}_1(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \vec{P}_{j,mn}^1,$$

$$\vec{H}_1(\vec{r}) = (1/2d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} (\vec{dl}_j \times \vec{k}_{mn}^1),$$

$$\vec{P}_{j,mn}^1 = \vec{k}_{mn}^1 \times (\vec{k}_{mn}^1 \times \vec{dl}_j), \quad \vec{k}_{mn}^1 = \vec{k}_{mn}^1 \{k_{n,x}, k_{m,y}, k_{mn,z}\}$$

da aseve

$$\vec{E}_2(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)} \vec{P}_{j,mn}^2,$$

$$\vec{H}_2(\vec{r}) = (1/2d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)} (\vec{dl}_j \times \vec{k}_{mn}^2),$$

$$\vec{P}_{j,mn}^2 = \vec{k}_{mn}^2 \times (\vec{k}_{mn}^2 \times \vec{dl}_j), \quad \vec{k}_{mn}^2 = \vec{k}_{mn}^2 \{k_{n,x}, k_{m,y}, -k_{mn,z}\}.$$

am gamosaxul ebebSi

$$\vec{dl}_j = dl_j \{dx_j, dy_j, 0\}, \quad |\vec{k}_{mn}^1| = |\vec{k}_{mn}^2| = k,$$

$$k_{n,x} = k_x + 2\pi n/d_1, \quad k_{m,y} = k_y + 2\pi m/d_2, \quad k_{mn,z} = \sqrt{k^2 - k_{n,x}^2 - k_{m,y}^2}.$$

gadavideT axl a danarCeni vel ebis gansazRvraxe yvel a areSi. pirvel areSi gagvaCnia  $\vec{E}_1(\vec{r})$  da dacemul i  $\vec{E}_{inc}(\vec{r})$  vel ebi (3.2.2).

$$\vec{E}_1(\vec{r}) + \vec{E}_{inc}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \vec{P}_{j,mn}^1 + \vec{E}_{inc}(\vec{r}). \quad (3.2.8)$$

unda aRiniSnos, rom diel eqtrikidan mesrisaken wamosul i harmonikis pol arizacia ganisazRvrebaba  $\vec{P}_{j,mn}^2$  veqtoriT, anu  $\vec{dl}_j$  da  $\vec{k}_{mn}^2$  veqtorebiT:

$$\vec{P}_{j,mn}^2 = \vec{k}_{mn}^2 \times (\vec{k}_{mn}^2 \times \vec{dl}_j) = \vec{k}_{mn}^2 (\vec{k}_{mn}^2 \cdot \vec{dl}_j) - k^2 \vec{dl}_j.$$

diel eqtrikul fenastan urTierTqmedebis Semdeg miRebul i vel ebis pol arizaciis veqtorebi unda imyofebodnen imave sibrtyeSi. amis gamo, maTi orientacia kvl av unda ganisazRvrebodes  $\vec{dl}_j$  da  $\vec{k}_{mn}^2$  veqtorebiT.

aRniSnul is gaTval iswinebiT, meore areSi vel is (3.2.3) gamosaxul eba veZeboT rogorc

$$\vec{E}_2(\vec{r}) + \vec{E}_e(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} \left( e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)} \vec{P}_{j,mn}^2 + e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \vec{R}_{j,mn} \right), \quad (3.2.9)$$

sadac

$$\vec{R}_{j,mn} = B_{j,mn} \vec{k}_{mn}^2 + C_{j,mn} \vec{d}_j,$$

$B_{j,mn}$  da  $C_{j,mn}$  ucnobi koeficientebia.

mesame areSi gagvačnia  $z = -h$  zedapiridan gardatexil i da  $z = -(h+d)$  zedapiridan arekvl il i vel ebi (3.2.4), roml ebsac veZebT Semdegi saxiT:

$$\vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) = (1/2\omega\varepsilon_0\varepsilon d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{\prime-1} \left( e^{i\vec{k}_{mn}^f \cdot (\vec{r}-\vec{r}_j)} \vec{Q}_{j,mn} + e^{i\vec{k}_{mn}^g \cdot (\vec{r}-\vec{r}_j)} \vec{S}_{j,mn} \right), \quad (3.2.10)$$

sadac

$$\vec{k}_{mn}^f = \vec{k}_{mn}^f \{k_{n,x}, k_{m,y}, -k'_{mn,z}\}, \quad \vec{k}_{mn}^g = \vec{k}_{mn}^g \{k_{n,x}, k_{m,y}, k'_{mn,z}\}, \quad k'_{mn,z} = \sqrt{k^2 \mu \varepsilon - k_{n,x}^2 - k_{m,y}^2},$$

$$\vec{Q}_{j,mn} = D_{j,mn} \vec{k}_{mn}^2 + F_{j,mn} \vec{d}_j, \quad \vec{S}_{j,mn} = G_{j,mn} \vec{k}_{mn}^2 + L_{j,mn} \vec{d}_j,$$

$D_{j,mn}$ ,  $F_{j,mn}$ ,  $G_{j,mn}$ ,  $L_{j,mn}$  ucnobi koeficientebia.

meoTxe areSi gagvačnia mxol od sistemidan gamosul i vel ebi (3.2.5), romel sac veZebT kvl av rogorc:

$$\vec{E}_s(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^2 \cdot (\vec{r}-\vec{r}_j)} \vec{T}_{j,mn}, \quad (3.2.11)$$

sadac

$$\vec{T}_{j,mn} = \Gamma_{j,mn} \vec{k}_{mn}^2 + Y_{j,mn} \vec{d}_j,$$

xol o  $\Gamma_{j,mn}$ ,  $Y_{j,mn}$  ucnob koeficientebis warmoadgenen.

magnitur vel s yvel a areSi vipoviT maqsvel is gantol ebidan

$$\vec{H}(\vec{r}) = -(i/\omega\mu_0\mu) \text{rot} \vec{E}(\vec{r}).$$

mi vi RebT:

$$\vec{H}_1(\vec{r}) + \vec{H}_{inc}(\vec{r}) = (1/2d_1 d_2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^1 \cdot (\vec{r}-\vec{r}_j)} (\vec{d}_j \times \vec{k}_{mn}^1) + \vec{H}_{inc}(\vec{r}), \quad (3.2.12)$$

$$\vec{H}_2(\vec{r}) + \vec{H}_e(\vec{r}) = (1/2d_1 d_2) \cdot$$

$$\sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} \left( e^{i\vec{k}_{mn}^2 \cdot (\vec{r}-\vec{r}_j)} (\vec{d}_j \times \vec{k}_{mn}^2) - (k^2)^{-1} e^{i\vec{k}_{mn}^1 \cdot (\vec{r}-\vec{r}_j)} (\vec{R}_{j,mn} \times \vec{k}_{mn}^1) \right), \quad (3.2.13)$$

$$\vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) = -(1/2d_1 d_2 k^2 \mu \varepsilon) \cdot$$

$$\sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{\prime-1} \left( e^{i\vec{k}_{mn}^f \cdot (\vec{r}-\vec{r}_j)} (\vec{Q}_{j,mn} \times \vec{k}_{mn}^f) + e^{i\vec{k}_{mn}^g \cdot (\vec{r}-\vec{r}_j)} (\vec{S}_{j,mn} \times \vec{k}_{mn}^g) \right), \quad (3.2.14)$$

$$\vec{H}_s(\vec{r}) = -(1/2d_1 d_2 k^2) \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z}^{-1} e^{i\vec{k}_{mn}^2 \cdot (\vec{r}-\vec{r}_j)} (\vec{T}_{j,mn} \times \vec{k}_{mn}^2). \quad (3.2.15)$$

maSasadame, gagvačnia Semdegi ucnobi koeficientebi:  $A_j$ ,  $B_{j,mn}$ ,  $C_{j,mn}$ ,  $D_{j,mn}$ ,  $F_{j,mn}$ ,  $G_{j,mn}$ ,  $L_{j,mn}$ ,  $\Gamma_{j,mn}$ ,  $Y_{j,mn}$  da maTi gansazRvra sasazRvro pirobedidan SeiZl eba.

ČavsvaT exl a vel is (3.2.8) – (3.2.15) gamosaxul ebebi (3.2.7) sasazRvro pirobedSi diel eqtrikis zedapirebze. pirvel pirobidan mi vi RebT:

$$\begin{aligned} & \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} k_{mn,z} e^{i(k_{n,x}(x-x_j) + k_{m,y}(y-y_j))} \left( e^{ik_{mn,z}h} \vec{P}_{j,mn}^2 + e^{-ik_{mn,z}h} \vec{R}_{j,mn} \right) \cdot \vec{x} = \\ & = \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} (\varepsilon k_{mn,z}^{\prime-1})^{-1} e^{i(k_{n,x}(x-x_j) + k_{m,y}(y-y_j))} \left( e^{ik_{mn,z}h} \vec{Q}_{j,mn} + e^{-ik_{mn,z}h} \vec{S}_{j,mn} \right) \cdot \vec{x}. \end{aligned}$$

es tol oba unda iyos samarTl iani nebismeri  $(x, y)$  wyvil isaTvis. mas mniSvnel ovnad gavamartivebT, Tu gaviTval iswinebT, rom funqciebi  $e^{i(k_{n,x}(x-x_j)+k_{m,y}(y-y_j))}$  hqmnian ortogonal ur sistemas  $\Delta_{d_1 \times d_2}$  marTkuTxedis fargl ebSi, sadac

$$\Delta_{d_1 \times d_2} = \left[ -d_1/2 + x_j, d_1/2 + x_j \right] \cup \left[ -d_2/2 + y_j, d_2/2 + y_j \right].$$

amisaTvis tol obis orive mxare gavamravl oT  $e^{-i(k_{p,x}(x-x_j)+k_{q,y}(y-y_j))}$  - ze, (sadac  $p$  da  $q$  fiqsirebul i mTel i ricxvebia) da Semdeg gavaintegroT  $\Delta_{d_1 \times d_2}$  areSi:

$$\begin{aligned} & \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \iint_{\Delta_{d_1 \times d_2}} e^{i((k_{n,x}-k_{p,x})(x-x_j)+(k_{m,y}-k_{q,y})(y-y_j))} dx dy \times k_{mn,z}^{-1} \left( e^{ik_{mn,z}h} \bar{P}_{j,mm}^2 + e^{-ik_{mn,z}h} \bar{R}_{j,mm} \right) \cdot \bar{x} = \\ & = \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \iint_{\Delta_{d_1 \times d_2}} e^{i((k_{n,x}-k_{p,x})(x-x_j)+(k_{m,y}-k_{q,y})(y-y_j))} dx dy \times (\varepsilon k'_{mn,z})^{-1} \left( e^{ik'_{mn,z}h} \bar{Q}_{j,mm} + e^{-ik'_{mn,z}h} \bar{S}_{j,mm} \right) \cdot \bar{x}. \end{aligned}$$

integriribis Sedegad vRebul obT, rom

$$\iint_{\Delta_{d_1 \times d_2}} e^{i((k_{n,x}-k_{p,x})(x-x_j)+(k_{m,y}-k_{q,y})(y-y_j))} dx dy = \frac{d_1 d_2 \sin \pi(n-p) \sin \pi(m-q)}{\pi^2(n-p)(m-q)} = \begin{cases} 0, n \neq p, (m \neq q) \\ d_1 d_2, n = p, m = q \end{cases}$$

es imas niSnavs, rom tol obis orive mxareSi, ormagi usasrul o j amisgan dagvrCeba mxol od is wevri, roml isaTvis  $n = p$  da  $m = q$ . mi vi RebT:

$$\sum_{j=1}^N A_j \left( k_{qp,z}^{-1} \left( e^{ik_{qp,z}h} \bar{P}_{j,qp}^2 + e^{-ik_{qp,z}h} \bar{R}_{j,qp} \right) - (\varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}h} \bar{Q}_{j,qp} + e^{-ik'_{qp,z}h} \bar{S}_{j,qp} \right) \right) \cdot \bar{x} = 0.$$

anal ogiurad, danarCen sasazRvro pirobebi dan, gveqneba:

$$\begin{aligned} & \sum_{j=1}^N A_j \left( k_{qp,z}^{-1} \left( (k^2)^{-1} e^{-ik_{qp,z}h} \left( \bar{R}_{j,qp} \times \bar{k}_{qp}^1 \right) - e^{ik_{qp,z}h} \left( d\bar{l}_j \times \bar{k}_{qp}^2 \right) \right) - \right. \\ & \left. - (k^2 \mu \varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}h} \left( \bar{Q}_{j,qp} \times \bar{k}_{qp}^f \right) + e^{-ik'_{qp,z}h} \left( \bar{S}_{j,qp} \times \bar{k}_{qp}^g \right) \right) \right) \cdot \bar{x} = 0, \end{aligned}$$

$$\sum_{j=1}^N A_j \left( k_{qp,z}^{-1} \left( e^{ik_{qp,z}h} \bar{P}_{j,qp}^2 + e^{-ik_{qp,z}h} \bar{R}_{j,qp} \right) - (\varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}h} \bar{Q}_{j,qp} + e^{-ik'_{qp,z}h} \bar{S}_{j,qp} \right) \right) \cdot \bar{y} = 0,$$

$$\begin{aligned} & \sum_{j=1}^N A_j \left( k_{qp,z}^{-1} \left( (k^2)^{-1} e^{-ik_{qp,z}h} \left( \bar{R}_{j,qp} \times \bar{k}_{qp}^1 \right) - e^{ik_{qp,z}h} \left( d\bar{l}_j \times \bar{k}_{qp}^2 \right) \right) - \right. \\ & \left. - (k^2 \mu \varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}h} \left( \bar{Q}_{j,qp} \times \bar{k}_{qp}^f \right) + e^{-ik'_{qp,z}h} \left( \bar{S}_{j,qp} \times \bar{k}_{qp}^g \right) \right) \right) \cdot \bar{y} = 0, \end{aligned}$$

$$\sum_{j=1}^N A_j \left( (\varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}(h+d)} \bar{Q}_{j,qp} + e^{-ik'_{qp,z}(h+d)} \bar{S}_{j,qp} \right) - k_{qp,z}^{-1} e^{ik_{qp,z}(h+d)} \bar{T}_{j,qp} \right) \cdot \bar{x} = 0,$$

$$\sum_{j=1}^N A_j \left( (\mu \varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}(h+d)} \left( \bar{Q}_{j,qp} \times \bar{k}_{qp}^f \right) + e^{-ik'_{qp,z}(h+d)} \left( \bar{S}_{j,qp} \times \bar{k}_{qp}^g \right) \right) - k_{qp,z}^{-1} e^{ik_{qp,z}(h+d)} \left( \bar{T}_{j,qp} \times \bar{k}_{qp}^2 \right) \right) \cdot \bar{x} = 0,$$

$$\sum_{j=1}^N A_j \left( (\varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}(h+d)} \bar{Q}_{j,qp} + e^{-ik'_{qp,z}(h+d)} \bar{S}_{j,qp} \right) - k_{qp,z}^{-1} e^{ik_{qp,z}(h+d)} \bar{T}_{j,qp} \right) \cdot \bar{y} = 0,$$

$$\sum_{j=1}^N A_j \left( (\mu \varepsilon k'_{qp,z})^{-1} \left( e^{ik'_{qp,z}(h+d)} \left( \bar{Q}_{j,qp} \times \bar{k}_{qp}^f \right) + e^{-ik'_{qp,z}(h+d)} \left( \bar{S}_{j,qp} \times \bar{k}_{qp}^g \right) \right) - k_{qp,z}^{-1} e^{ik_{qp,z}(h+d)} \left( \bar{T}_{j,qp} \times \bar{k}_{qp}^2 \right) \right) \cdot \bar{y} = 0.$$

mivaqciot axl a yuradReba imas, rom amave sasazRvro pirobebs unda akmayofil ebdnen ara mxol od j amuri vel ebi, aramed aseve cal keul i  $A_j$

denis mier Seqmnil i vel ebi. Tu gaviTval iswinebT naTqvams da gamovi yenebT aseve  $\vec{R}_{j,qp}$ ,  $\vec{Q}_{j,qp}$ ,  $\vec{S}_{j,qp}$ ,  $\vec{T}_{j,qp}$  veqtorebis gamosaxul ebebs, maSin ucnobi  $B_{j,qp}$ ,  $C_{j,qp}$ ,  $D_{j,qp}$ ,  $F_{j,qp}$ ,  $G_{j,qp}$ ,  $L_{j,qp}$ ,  $\Gamma_{j,qp}$ ,  $Y_{j,qp}$  koeficientebis mimaT miviRebT wrfiv gantol ebaTa sistemas:

$$\begin{aligned}
& e^{-ik_{qp,z}h} \left( B_{j,qp} k_{p,x} + C_{j,qp} dx_j \right) - \left( k_{qp,z} / \varepsilon k'_{qp,z} \right) e^{ik'_{qp,z}h} \left( D_{j,qp} k_{p,x} + F_{j,qp} dx_j \right) - \\
& \quad - \left( k_{qp,z} / \varepsilon k'_{qp,z} \right) e^{-ik'_{qp,z}h} \left( G_{j,qp} k_{p,x} + L_{j,qp} dx_j \right) = -e^{ik_{qp,z}h} \left( \vec{P}_{j,qp}^2 \cdot \vec{x} \right), \\
& \mu \varepsilon k'_{qp,z} e^{-ik_{qp,z}h} \left( 2B_{j,qp} k_{q,y} + C_{j,qp} dy_j \right) - \\
& \quad - e^{ik'_{qp,z}h} \left( D_{j,qp} k_{q,y} \left( k_{qp,z} - k'_{qp,z} \right) - F_{j,qp} k'_{qp,z} dy_j \right) - \\
& \quad - e^{-ik'_{qp,z}h} \left( G_{j,qp} k_{q,y} \left( k_{qp,z} + k'_{qp,z} \right) + L_{j,qp} k'_{qp,z} dy_j \right) = -k^2 \mu \varepsilon k'_{qp,z} e^{ik_{qp,z}h} dy_j, \\
& e^{-ik_{qp,z}h} \left( B_{j,qp} k_{q,y} + C_{j,qp} dy_j \right) - \left( k_{qp,z} / \varepsilon k'_{qp,z} \right) e^{ik'_{qp,z}h} \left( D_{j,qp} k_{q,y} + F_{j,qp} dy_j \right) - \\
& \quad - \left( k_{qp,z} / \varepsilon k'_{qp,z} \right) e^{-ik'_{qp,z}h} \left( G_{j,qp} k_{q,y} + L_{j,qp} dy_j \right) = -e^{ik_{qp,z}h} \left( \vec{P}_{j,qp}^2 \cdot \vec{y} \right), \\
& \mu \varepsilon k'_{qp,z} e^{-ik_{qp,z}h} \left( 2B_{j,qp} k_{p,x} + C_{j,qp} dx_j \right) - \\
& \quad - e^{ik'_{qp,z}h} \left( D_{j,qp} k_{p,x} \left( k_{qp,z} - k'_{qp,z} \right) - F_{j,qp} k'_{qp,z} dx_j \right) - \\
& \quad - e^{-ik'_{qp,z}h} \left( G_{j,qp} k_{p,x} \left( k_{qp,z} + k'_{qp,z} \right) + L_{j,qp} k'_{qp,z} dx_j \right) = -k^2 \mu \varepsilon k'_{qp,z} e^{ik_{qp,z}h} dx_j \\
& e^{ik'_{qp,z}(h+d)} \left( D_{j,qp} k_{p,x} + F_{j,qp} dx_j \right) + \\
& \quad + e^{-ik'_{qp,z}(h+d)} \left( G_{j,qp} k_{p,x} + L_{j,qp} dx_j \right) - \left( \varepsilon k'_{qp,z} / k_{qp,z} \right) e^{ik_{qp,z}(h+d)} \left( \Gamma_{j,qp} k_{p,x} + Y_{j,qp} dx_j \right) = 0' \\
& e^{ik'_{qp,z}(h+d)} \left( D_{j,qp} k_{q,y} \left( k_{qp,z} - k'_{qp,z} \right) - F_{j,qp} k'_{qp,z} dy_j \right) + \\
& \quad + e^{-ik'_{qp,z}(h+d)} \left( G_{j,qp} k_{q,y} \left( k_{qp,z} + k'_{qp,z} \right) + L_{j,qp} k'_{qp,z} dy_j \right) = -\mu \varepsilon k'_{qp,z} e^{ik_{qp,z}(h+d)} Y_{j,qp} dy_j \\
& e^{ik'_{qp,z}(h+d)} \left( D_{j,qp} k_{q,y} + F_{j,qp} dy_j \right) + \\
& \quad + e^{-ik'_{qp,z}(h+d)} \left( G_{j,qp} k_{q,y} + L_{j,qp} dy_j \right) - \left( \varepsilon k'_{qp,z} / k_{qp,z} \right) e^{ik_{qp,z}(h+d)} \left( \Gamma_{j,qp} k_{q,y} + Y_{j,qp} dy_j \right) = 0 \\
& e^{ik'_{qp,z}(h+d)} \left( D_{j,qp} k_{p,x} \left( k_{qp,z} - k'_{qp,z} \right) - F_{j,qp} k'_{qp,z} dx_j \right) + \\
& \quad + e^{-ik'_{qp,z}(h+d)} \left( G_{j,qp} k_{p,x} \left( k_{qp,z} + k'_{qp,z} \right) + L_{j,qp} k'_{qp,z} dx_j \right) = -\mu \varepsilon k'_{qp,z} e^{ik_{qp,z}(h+d)} Y_{j,qp} dx_j.
\end{aligned}$$

am sistemis pirdapiri amoxsna garkveul sirTul es warmoadgens. amitom ufro martivia misi amoxsna kompiuterul i model irebis saSual ebiT.

amoxsnis Semdeg ucnobi rCeba mxol od  $A_j$  denis ampl itudebi mesris el ementSi da maTi gansazRvra (3.2.6) sasazRvro pirobidan SeiZl eba. el ementi warmodgenil ia rogoc segmentebis erTobl ioba da es sasazRvro piroba yovel aseT segmentze unda srul debodes:

$$\left( \vec{E}_{inc}(\vec{r}_\sigma) + \vec{E}_1(\vec{r}_\sigma) + \vec{E}_e(\vec{r}_\sigma) \right) \cdot d\vec{l}_\sigma = 0, \quad \sigma = 1, 2, \dots, N.$$

aq  $\vec{r}_\sigma = \vec{r}_\sigma \{x_\sigma, y_\sigma, dr_\sigma\}$  warmoadgens  $d\vec{l}_\sigma$  segmentis zedapirze aRebul i wertil is radiusveqtore. es bol o gamosaxul eba aseve gantol ebaTa sistemas warmoadgens da misi amoxsna kvl av kompiuteris saSual ebiT SeiZl eba.

amis Semdeg napovnia yvel a ucnobi koeficienti da maTi CasmiT vel ebis gamosaxul ebaSi, vpoul obT vel ebis mniSvel obebs yvel a areSi.

Semdeg ganixil eba dasmul i amocanis amoxsnis sxva gza. amisaTvis mesridan diel eqtrikisaken mimaval i  $\vec{E}_2(\vec{r})$ ,  $\vec{H}_2(\vec{r})$  vel is magivrad ganixil eba mxol od misi erTi harmonika da Seswavl il ia am harmonikis urTierTqmedeba am diel eqtrikTan. garda amisa, am harmonikis pol arizaciis veqtori daSl il ia or mdgenel ad. pirveli mdgenel i imyofeba dacemis sibrtyeSi, xol o meore – am sibrtiyis marTobul ia. Seswavl il ia cal -cal ke am ori vel is difraqcia diel eqtrikul fenaze da gabneul i vel is ampl itudebi kvl av sasazRvro pirobebidan ganisazRvrebA.

**pol arizaciis veqtoris daSl a paral el ur da marTobul mdgenel ebad.** ganvixil oT mesridan diel eqtrikul fenisaken mimaval i erTerTi harmonika:

$$\vec{E}_{j,mn}(\vec{r}) = (1/2\omega\varepsilon_0 d_1 d_2) k_{mn,z}^{-1} e^{ik_{mn}^2(\vec{r}-\vec{r}_j)} \vec{P}_{j,mn}^2,$$

$$\vec{H}_{j,mn}(\vec{r}) = (1/2d_1 d_2) k_{mn,z}^{-1} e^{ik_{mn}^2(\vec{r}-\vec{r}_j)} (\vec{d}\vec{l}_j \times \vec{k}_{mn}^2) = (1/2d_1 d_2 k^2) k_{mn,z}^{-1} e^{ik_{mn}^2(\vec{r}-\vec{r}_j)} (\vec{k}_{mn}^2 \times \vec{P}_{j,mn}^2),$$

sadac

$$\vec{P}_{j,mn}^2 = \vec{k}_{mn}^2 \times (\vec{k}_{mn}^2 \times \vec{d}\vec{l}_j) = \vec{k}_{mn}^2 (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 \vec{d}\vec{l}_j -$$

am harmonikis pol arizaciis veqtoria. gasagebia, rom srul i vel i aris aseTi harmonikebis j ami:

$$\vec{E}_2(\vec{r}) = \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \vec{E}_{j,mn}(\vec{r}), \quad \vec{H}_2(\vec{r}) = \sum_{j=1}^N A_j \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \vec{H}_{j,mn}(\vec{r}).$$

warmovidginoT axl a  $\vec{P}_{j,mn}^2$  veqtori, rogorc  $\vec{P}_{j,mn}^2 = \vec{P}_{j,mn,\parallel}^2 + \vec{P}_{j,mn,\perp}^2$ , sadac  $\vec{P}_{j,mn,\parallel}^2$  imyofeba imave sibrtyeSi, romel Sicaa  $\vec{k}_{mn}^2$  da  $\vec{z}$  ortveqtori (dacemis sibrtye), xol o  $\vec{P}_{j,mn,\perp}^2$  am sibrtiyis marTobul ia.

naTqvamis Tanaxmad es veqtorebi unda akmayofil ebdnen Semdeg pirobebs:

$$(\vec{P}_{j,mn,\parallel}^2 \times \vec{k}_{mn}^2) \cdot \vec{z} = 0, \quad \vec{P}_{j,mn,\perp}^2 \cdot \vec{k}_{mn}^2 = 0, \quad \vec{P}_{j,mn,\perp}^2 \cdot \vec{z} = 0.$$

gavSal oT  $\vec{P}_{j,mn,\parallel}^2$  da  $\vec{P}_{j,mn,\perp}^2$  veqtorebi  $\vec{x}, \vec{y}, \vec{z}$  bazisSi:

$$\vec{P}_{j,mn,\parallel}^2 = a_{j,mn,x} \vec{x} + a_{j,mn,y} \vec{y} + a_{j,mn,z} \vec{z}, \quad \vec{P}_{j,mn,\perp}^2 = b_{j,mn,x} \vec{x} + b_{j,mn,y} \vec{y} + b_{j,mn,z} \vec{z}.$$

maSin moyvanil pirobebidan, gaSl is ucnob koeficientebis mimarT vRebul obT

$$a_{j,mn,x} k_{m,y} - a_{j,mn,y} k_{n,x} = 0, \quad b_{j,mn,x} k_{n,x} + b_{j,mn,y} k_{m,y} = 0, \quad b_{j,mn,z} = 0$$

da aqedan

$$a_{j,mn,y} = (k_{m,y}/k_{n,x}) a_{j,mn,x}, \quad b_{j,mn,y} = -(k_{n,x}/k_{m,y}) b_{j,mn,x}, \quad b_{j,mn,z} = 0.$$

maSasadame,

$$\vec{P}_{j,mn,\parallel}^2 = a_{j,mn,x} \vec{x} + (k_{m,y}/k_{n,x}) a_{j,mn,x} \vec{y} + a_{j,mn,z} \vec{z}, \quad \vec{P}_{j,mn,\perp}^2 = b_{j,mn,x} \vec{x} - (k_{n,x}/k_{m,y}) b_{j,mn,x} \vec{y},$$

sai danac

$$\vec{P}_{j,mn}^2 = (a_{j,mn,x} + b_{j,mn,x}) \vec{x} + ((k_{m,y}/k_{n,x}) a_{j,mn,x} - (k_{n,x}/k_{m,y}) b_{j,mn,x}) \vec{y} + a_{j,mn,z} \vec{z}.$$

magram,  $\vec{P}_{j,mn}^2$  veqtoris gamosaxul ebidan gamomdinareobs, rom

$$\vec{P}_{j,mn}^2 = (k_{n,x} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 dx_j) \vec{x} + (k_{m,y} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 dy_j) \vec{y} - k_{mn,z} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) \vec{z}$$



da ami tom unda srul debodes Semdegi pi robebi

$$\begin{cases} a_{j,mn,x} + b_{j,mn,x} = k_{n,x} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 dx_j \\ (k_{m,y}/k_{n,x}) a_{j,mn,x} - (k_{n,x}/k_{m,y}) b_{j,mn,x} = k_{m,y} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 dy_j \\ a_{j,mn,z} = -k_{mn,z} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j). \end{cases}$$

am sistemis amoxsnis Sedegad viciT ukve yvel a koeficientebi:

$$\begin{aligned} a_{j,mn,x} &= k_{n,x} \left(1 - k^2 (k_{n,x}^2 + k_{m,y}^2)^{-1}\right) (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j), \quad a_{j,mn,y} = k_{m,y} \left(1 - k^2 (k_{n,x}^2 + k_{m,y}^2)^{-1}\right) (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j), \\ a_{j,mn,z} &= -k_{mn,z} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j), \quad b_{j,mn,x} = k^2 \left(k_{n,x} (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - dx_j\right), \\ b_{j,mn,y} &= -k^2 \left(k_{n,x}/k_{m,y}\right) \left(k_{n,x} (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - dx_j\right), \quad b_{j,mn,z} = 0. \end{aligned}$$

aqedan gamomdinare,

$$\begin{aligned} \vec{P}_{j,mn,\parallel}^2 &= \vec{k}_{mn}^2 (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - k^2 (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) (k_{n,x} \vec{x} + k_{m,y} \vec{y}) \\ \vec{P}_{j,mn,\perp}^2 &= k^2 \left(k_{n,x} (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^2 \cdot \vec{d}\vec{l}_j) - dx_j\right) (\vec{x} - (k_{n,x}/k_{m,y}) \vec{y}). \end{aligned}$$

**dasmul i amocanis amoxsnis meore meTodi.** Cven unda amovxsnat difraqciis amocana cal keul harmoniki saTvis. amisaTvis dacemul i harmonikis gamosaxul ebaSi  $\vec{P}_{j,mn}^2$  veqtori warmovidginoT zeviT moyvani i j amis saxiT. mi vi RebT:

$$\vec{E}_{j,mn}(\vec{r}) = \vec{E}_{j,mn,\parallel}^0 e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)} + \vec{E}_{j,mn,\perp}^0 e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)}, \quad \vec{H}_{j,mn}(\vec{r}) = \vec{H}_{j,mn,\perp}^0 e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)} + \vec{H}_{j,mn,\parallel}^0 e^{i\vec{k}_{mn}^2 \cdot (\vec{r} - \vec{r}_j)},$$

sadac

$$\begin{aligned} \vec{E}_{j,mn,\parallel}^0 &= (1/2\omega\varepsilon_0 d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\parallel}^2, \quad \vec{E}_{j,mn,\perp}^0 = (1/2\omega\varepsilon_0 d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\perp}^2, \\ \vec{H}_{j,mn,\perp}^0 &= (1/2d_1 d_2 k^2) k_{mn,z}^{-1} (\vec{k}_{mn}^2 \times \vec{P}_{j,mn,\parallel}^2), \quad \vec{H}_{j,mn,\parallel}^0 = (1/2d_1 d_2 k^2) k_{mn,z}^{-1} (\vec{k}_{mn}^2 \times \vec{P}_{j,mn,\perp}^2). \end{aligned}$$

es Canaweri gvaZl evs saSual ebas dawweroT anal ogiuri gamosaxul ebebi danarCen ucnoB difragirebul vel ebisaTvis. marTI ac,

1. arekvl il vel s unda gaaCndes Semdegi saxe:

$$\begin{aligned} \vec{E}_{j,mn}^e(\vec{r}) &= \vec{E}_{j,mn,\parallel}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} + \vec{E}_{j,mn,\perp}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)}, \quad \vec{H}_{j,mn}^e(\vec{r}) = \vec{H}_{j,mn,\perp}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} + \vec{H}_{j,mn,\parallel}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \\ \vec{E}_{j,mn,\parallel}^{0,e} &= R_{j,mn,\parallel} (1/2\omega\varepsilon_0 d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\parallel}^1, \quad \vec{E}_{j,mn,\perp}^{0,e} = R_{j,mn,\perp} (1/2\omega\varepsilon_0 d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\perp}^1, \\ \vec{H}_{j,mn,\perp}^{0,e} &= R_{j,mn,\parallel} (1/2d_1 d_2 k^2) k_{mn,z}^{-1} (\vec{k}_{mn}^1 \times \vec{P}_{j,mn,\parallel}^1), \quad \vec{H}_{j,mn,\parallel}^{0,e} = R_{j,mn,\perp} (1/2d_1 d_2 k^2) k_{mn,z}^{-1} (\vec{k}_{mn}^1 \times \vec{P}_{j,mn,\perp}^1), \end{aligned}$$

sadac anal ogiurad

$$\begin{aligned} \vec{P}_{j,mn,\parallel}^1 &= \vec{k}_{mn}^1 (\vec{k}_{mn}^1 \cdot \vec{d}\vec{l}_j) - k^2 (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^1 \cdot \vec{d}\vec{l}_j) (k_{n,x} \vec{x} + k_{m,y} \vec{y}) \\ \vec{P}_{j,mn,\perp}^1 &= k^2 \left(k_{n,x} (k_{n,x}^2 + k_{m,y}^2)^{-1} (\vec{k}_{mn}^1 \cdot \vec{d}\vec{l}_j) - dx_j\right) (\vec{x} - (k_{n,x}/k_{m,y}) \vec{y}), \end{aligned}$$

xol o  $R_{j,mn,\parallel}$  da  $R_{j,mn,\perp}$  arekvl is ucnoBi koeficientebia.

2. gardatexil i vel istvis gveqneba

$$\begin{aligned} \vec{E}_{j,mn}^f(\vec{r}) &= \vec{E}_{j,mn,\parallel}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} + \vec{E}_{j,mn,\perp}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)}, \quad \vec{H}_{j,mn}^f(\vec{r}) = \vec{H}_{j,mn,\perp}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} + \vec{H}_{j,mn,\parallel}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)}, \\ \vec{E}_{j,mn,\parallel}^{0,f} &= A_{j,mn,\parallel} (1/2\omega\varepsilon_0 \varepsilon d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\parallel}^f, \quad \vec{E}_{j,mn,\perp}^{0,f} = A_{j,mn,\perp} (1/2\omega\varepsilon_0 \varepsilon d_1 d_2) k_{mn,z}^{-1} \vec{P}_{j,mn,\perp}^f, \end{aligned}$$

$$\begin{aligned}\vec{H}_{j,mn,\perp}^{0,f} &= A_{j,mn,\parallel} \left( \frac{1}{2} d_1 d_2 \varepsilon \mu k^2 \right) k_{mn,z}^{\prime-1} \left( \vec{k}_{mn}^f \times \vec{P}_{j,mn,\parallel}^f \right), \quad \vec{H}_{j,mn,\parallel}^{0,f} = A_{j,mn,\perp} \left( \frac{1}{2} d_1 d_2 \varepsilon \mu k^2 \right) k_{mn,z}^{\prime-1} \left( \vec{k}_{mn}^f \times \vec{P}_{j,mn,\perp}^f \right), \\ \vec{P}_{j,mn,\parallel}^f &= \vec{k}_{mn}^f \left( \vec{k}_{mn}^f \cdot d\vec{l}_j \right) - \varepsilon \mu k^2 \left( k_{n,x}^2 + k_{m,y}^2 \right)^{-1} \left( \vec{k}_{mn}^f \cdot d\vec{l}_j \right) \left( k_{n,x} \vec{x} + k_{m,y} \vec{y} \right), \\ \vec{P}_{j,mn,\perp}^f &= \varepsilon \mu k^2 \left( k_{n,x} \left( k_{n,x}^2 + k_{m,y}^2 \right)^{-1} \left( \vec{k}_{mn}^f \cdot d\vec{l}_j \right) - dx_j \right) \left( \vec{x} - \left( k_{n,x} / k_{m,y} \right) \vec{y} \right),\end{aligned}$$

sadac  $A_{j,mn,\parallel}$  da  $A_{j,mn,\perp}$  gardatexis ucno bi koeficientebia.

3. fenis SigniT arekvl il i vel i:

$$\begin{aligned}\vec{E}_{j,mn}^g(\vec{r}) &= \vec{E}_{j,mn,\parallel}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} + \vec{E}_{j,mn,\perp}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)}, \quad \vec{H}_{j,mn}^g(\vec{r}) = \vec{H}_{j,mn,\perp}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} + \vec{H}_{j,mn,\parallel}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)}, \\ \vec{E}_{j,mn,\parallel}^{0,g} &= B_{j,mn,\parallel} \left( \frac{1}{2} \omega \varepsilon_0 \varepsilon d_1 d_2 \right) k_{mn,z}^{\prime-1} \vec{P}_{j,mn,\parallel}^g, \quad \vec{E}_{j,mn,\perp}^{0,g} = B_{j,mn,\perp} \left( \frac{1}{2} \omega \varepsilon_0 \varepsilon d_1 d_2 \right) k_{mn,z}^{\prime-1} \vec{P}_{j,mn,\perp}^g, \\ \vec{H}_{j,mn,\perp}^{0,g} &= B_{j,mn,\parallel} \left( \frac{1}{2} d_1 d_2 \varepsilon \mu k^2 \right) k_{mn,z}^{\prime-1} \left( \vec{k}_{mn}^g \times \vec{P}_{j,mn,\parallel}^g \right), \quad \vec{H}_{j,mn,\parallel}^{0,g} = B_{j,mn,\perp} \left( \frac{1}{2} d_1 d_2 \varepsilon \mu k^2 \right) k_{mn,z}^{\prime-1} \left( \vec{k}_{mn}^g \times \vec{P}_{j,mn,\perp}^g \right), \\ \vec{P}_{j,mn,\parallel}^g &= \vec{k}_{mn}^g \left( \vec{k}_{mn}^g \cdot d\vec{l}_j \right) - \varepsilon \mu k^2 \left( k_{n,x}^2 + k_{m,y}^2 \right)^{-1} \left( \vec{k}_{mn}^g \cdot d\vec{l}_j \right) \left( k_{n,x} \vec{x} + k_{m,y} \vec{y} \right), \\ \vec{P}_{j,mn,\perp}^g &= \varepsilon \mu k^2 \left( k_{n,x} \left( k_{n,x}^2 + k_{m,y}^2 \right)^{-1} \left( \vec{k}_{mn}^g \cdot d\vec{l}_j \right) - dx_j \right) \left( \vec{x} - \left( k_{n,x} / k_{m,y} \right) \vec{y} \right),\end{aligned}$$

sadac  $B_{j,mn,\parallel}$  da  $B_{j,mn,\perp}$  Sida arekvl is ucno bi koeficientebia.

4. gasul i vel i:

$$\begin{aligned}\vec{E}_{j,mn}^s(\vec{r}) &= \vec{E}_{j,mn,\parallel}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)} + \vec{E}_{j,mn,\perp}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)}, \quad \vec{H}_{j,mn}^s(\vec{r}) = \vec{H}_{j,mn,\perp}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)} + \vec{H}_{j,mn,\parallel}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)}, \\ \vec{E}_{j,mn,\parallel}^{0,s} &= T_{j,mn,\parallel} \left( \frac{1}{2} \omega \varepsilon_0 d_1 d_2 \right) k_{mn,z}^{-1} \vec{P}_{j,mn,\parallel}^s, \quad \vec{E}_{j,mn,\perp}^{0,s} = T_{j,mn,\perp} \left( \frac{1}{2} \omega \varepsilon_0 d_1 d_2 \right) k_{mn,z}^{-1} \vec{P}_{j,mn,\perp}^s, \\ \vec{H}_{j,mn,\perp}^{0,s} &= T_{j,mn,\parallel} \left( \frac{1}{2} d_1 d_2 k^2 \right) k_{mn,z}^{-1} \left( \vec{k}_{mn}^s \times \vec{P}_{j,mn,\parallel}^s \right), \quad \vec{H}_{j,mn,\parallel}^{0,s} = T_{j,mn,\perp} \left( \frac{1}{2} d_1 d_2 k^2 \right) k_{mn,z}^{-1} \left( \vec{k}_{mn}^s \times \vec{P}_{j,mn,\perp}^s \right),\end{aligned}$$

sadac  $T_{j,mn,\parallel}$  da  $T_{j,mn,\perp}$  ucno bi koeficientebia.

maSasadame, gagvaCnia ori damoukidebel i tal Ra: pirvel i tal Ra:  $\vec{E}_{j,mn,\parallel}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)}$ ,  $\vec{H}_{j,mn,\perp}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)}$ , romel ic pol arizebul ia dacemis sibrtyeSi da aseve meore tal Ra:  $\vec{E}_{j,mn,\perp}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)}$ ,  $\vec{H}_{j,mn,\parallel}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)}$ , romel ic dacemis sibrtysis marTobul adaa pol arizebul i. cal -cal ke Seviswavl oT am tal Rebis urTierTqmedeba diel eqtrikul fenastAn.

**dacemis sibrtyeSi pol arizebul i tal Ra.** am tal Ris difraqciis dros, diel eqtrikis zedapirebze unda srul debodnen Semdegi sasazRvro pirobebi:

$$\left\{ \begin{aligned} \left( E_{j,mn,\parallel}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)} - E_{j,mn,\parallel}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-h} \cos \vartheta &= \left( E_{j,mn,\parallel}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} - E_{j,mn,\parallel}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-h} \cos \psi \\ \left( E_{j,mn,\parallel}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} - E_{j,mn,\parallel}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-(h+l)} \cos \psi &= E_{j,mn,\parallel}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)} \Big|_{z=-(h+l)} \cos \vartheta \\ \left( H_{j,mn,\perp}^0 e^{i\vec{k}_{mn}^0 \cdot (\vec{r} - \vec{r}_j)} + H_{j,mn,\perp}^{0,e} e^{i\vec{k}_{mn}^1 \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-h} &= \left( H_{j,mn,\perp}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} + H_{j,mn,\perp}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-h} \\ \left( H_{j,mn,\perp}^{0,f} e^{i\vec{k}_{mn}^f \cdot (\vec{r} - \vec{r}_j)} + H_{j,mn,\perp}^{0,g} e^{i\vec{k}_{mn}^g \cdot (\vec{r} - \vec{r}_j)} \right) \Big|_{z=-(h+l)} &= H_{j,mn,\perp}^{0,s} e^{i\vec{k}_{mn}^s \cdot (\vec{r} - \vec{r}_j)} \Big|_{z=-(h+l)}. \end{aligned} \right.$$

moyvanil i sistema garkveul i gamartivebis Semdeg Caiwereba rogorc

$$\begin{cases} \left( E_{j,mn,\parallel}^0 e^{ik_{mn,z}h} - E_{j,mn,\parallel}^{0,e} e^{-ik_{mn,z}h} \right) \cos \vartheta = \left( E_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}h} - E_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}h} \right) \cos \psi \\ \left( E_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}(h+1)} - E_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}(h+1)} \right) \cos \psi = E_{j,mn,\parallel}^{0,s} e^{ik_{mn,z}(h+1)} \cos \vartheta \\ H_{j,mn,\perp}^0 e^{ik_{mn,z}h} + H_{j,mn,\perp}^{0,e} e^{-ik_{mn,z}h} = H_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}h} + H_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}h} \\ H_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}(h+1)} + H_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}(h+1)} = H_{j,mn,\perp}^{0,s} e^{ik_{mn,z}(h+1)}. \end{cases}$$

aq  $\vartheta$  da  $\psi$  Sesabamisad dacemis da gardatexis kuTxebia. SeiZl eba naCveneb iqnas, rom am gamosaxul ebebdan gamomdinareobs Semdegi damoki debul ebebi vel is ampl itudebs Soris:

$$H_{j,mn,\perp}^0 = E_{j,mn,\parallel}^0 / Z, \quad H_{j,mn,\perp}^{0,e} = E_{j,mn,\parallel}^{0,e} / Z, \quad H_{j,mn,\perp}^{0,f} = E_{j,mn,\parallel}^{0,f} / Z', \\ H_{j,mn,\perp}^{0,g} = E_{j,mn,\parallel}^{0,g} / Z', \quad H_{j,mn,\perp}^{0,s} = E_{j,mn,\parallel}^{0,s} / Z',$$

sadac  $Z = \sqrt{\mu_0 / \varepsilon_0}$ ,  $Z' = \sqrt{\mu_0 \mu / \varepsilon_0 \varepsilon}$  Tavisufal i sivrcis da diel eqtrikis tal Ruri winaRobebia. amitom sistema sabol ood Caiwereba rogorc

$$\begin{cases} E_{j,mn,\parallel}^0 e^{ik_{mn,z}h} - E_{j,mn,\parallel}^{0,e} e^{-ik_{mn,z}h} = (\cos \psi / \cos \vartheta) \left( E_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}h} - E_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}h} \right) \\ E_{j,mn,\parallel}^{0,s} e^{ik_{mn,z}(h+1)} = (\cos \psi / \cos \vartheta) \left( E_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}(h+1)} - E_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}(h+1)} \right) \\ E_{j,mn,\perp}^0 e^{ik_{mn,z}h} + E_{j,mn,\perp}^{0,e} e^{-ik_{mn,z}h} = (Z/Z') \left( E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}h} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}h} \right) \\ E_{j,mn,\perp}^{0,s} e^{ik_{mn,z}(h+1)} = (Z/Z') \left( E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}(h+1)} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}(h+1)} \right). \end{cases}$$

Tu Semovi RebT aRni Svnebs

$$\tilde{Z}' = Z' \cos \psi + Z \cos \vartheta, \quad \tilde{Z} = Z' \cos \psi - Z \cos \vartheta,$$

maSin am sistemis amonaxsni iqneba

$$E_{j,mn,\parallel}^{0,e} = E_{j,mn,\parallel}^0 \tilde{Z}' \tilde{Z} \left( \tilde{Z}'^2 - \tilde{Z}^2 e^{2ik'_{mn,z}l} \right)^{-1} \left( e^{2ik'_{mn,z}l} - 1 \right) e^{2ik_{mn,z}h}, \\ E_{j,mn,\parallel}^{0,f} = E_{j,mn,\parallel}^0 \left( \cos \vartheta / \cos \psi \right) \tilde{Z}' \left( \tilde{Z}' + \tilde{Z} \right) \left( \tilde{Z}'^2 - \tilde{Z}^2 e^{2ik'_{mn,z}l} \right)^{-1} e^{i(k_{mn,z} - k'_{mn,z})h}, \\ E_{j,mn,\parallel}^{0,g} = E_{j,mn,\parallel}^0 \left( \cos \vartheta / \cos \psi \right) \tilde{Z} \left( \tilde{Z}' + \tilde{Z} \right) \left( \tilde{Z}'^2 - \tilde{Z}^2 e^{2ik'_{mn,z}l} \right)^{-1} e^{i(k_{mn,z} + k'_{mn,z})h + 2ik'_{mn,z}l}, \\ E_{j,mn,\parallel}^{0,s} = E_{j,mn,\parallel}^0 \left( \tilde{Z}'^2 - \tilde{Z}^2 \right) \left( \tilde{Z}'^2 - \tilde{Z}^2 e^{2ik'_{mn,z}l} \right)^{-1} e^{i(k'_{mn,z} - k_{mn,z})l}.$$

**dacemis sibrtiyis marTobul ad pol arizebul i tal Ra. misTvis,**  
sasazRvro pirobebi gvaZl evs sxva gantol ebaTa sistemas

$$\begin{cases} E_{j,mn,\perp}^0 e^{ik_{mn,z}h} + E_{j,mn,\perp}^{0,e} e^{-ik_{mn,z}h} = E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}h} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}h} \\ E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}(h+1)} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}(h+1)} = E_{j,mn,\perp}^{0,s} e^{ik_{mn,z}(h+1)} \\ \left( H_{j,mn,\parallel}^0 e^{ik_{mn,z}h} - H_{j,mn,\parallel}^{0,e} e^{-ik_{mn,z}h} \right) \cos \vartheta = \left( H_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}h} - H_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}h} \right) \cos \psi \\ \left( H_{j,mn,\parallel}^{0,f} e^{ik'_{mn,z}(h+1)} - H_{j,mn,\parallel}^{0,g} e^{-ik'_{mn,z}(h+1)} \right) \cos \psi = H_{j,mn,\parallel}^{0,s} e^{ik_{mn,z}(h+1)} \cos \vartheta. \end{cases}$$

aqac SeiZl eba naCveneb iqnas, rom magnituri da el eqtrul i vel is ampl itudebi Sesabamisi garemos tal Ruri winaRobebi T gansxvavdebian:

$$H_{j,mn,\parallel}^0 = E_{j,mn,\perp}^0 / Z, \quad H_{j,mn,\parallel}^{0,e} = E_{j,mn,\perp}^{0,e} / Z, \quad H_{j,mn,\parallel}^{0,f} = E_{j,mn,\perp}^{0,f} / Z', \\ H_{j,mn,\parallel}^{0,g} = E_{j,mn,\perp}^{0,g} / Z', \quad H_{j,mn,\parallel}^{0,s} = E_{j,mn,\perp}^{0,s} / Z',$$

$$Z = \sqrt{\mu_0/\varepsilon_0}, \quad Z' = \sqrt{\mu\mu_0/\varepsilon\varepsilon_0}.$$

ami tom zemoT moyvanil i sistema mi iRebs Semdeg sabol oo saxes:

$$\begin{cases} E_{j,mn,\perp}^0 e^{ik_{mn,z}h} + E_{j,mn,\perp}^{0,e} e^{-ik_{mn,z}h} = E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}h} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}h} \\ E_{j,mn,\perp}^{0,s} e^{ik_{mn,z}(h+l)} = E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}(h+l)} + E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}(h+l)} \\ E_{j,mn,\perp}^0 e^{ik_{mn,z}h} - E_{j,mn,\perp}^{0,e} e^{-ik_{mn,z}h} = (Z \cos \psi / Z' \cos \vartheta) (E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}h} - E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}h}) \\ E_{j,mn,\perp}^{0,s} e^{ik_{mn,z}(h+l)} = (Z \cos \psi / Z' \cos \vartheta) (E_{j,mn,\perp}^{0,f} e^{ik'_{mn,z}(h+l)} - E_{j,mn,\perp}^{0,g} e^{-ik'_{mn,z}(h+l)}). \end{cases}$$

Tu Semovi RebT aRni Svnebs

$$\bar{Z}' = Z \cos \psi + Z' \cos \vartheta, \quad \bar{Z} = Z \cos \psi - Z' \cos \vartheta,$$

maSin am sistemis amonaxsns eqneba Semdegi saxe:

$$\begin{aligned} E_{j,mn,\perp}^{0,e} &= E_{j,mn,\perp}^0 \bar{Z}' \bar{Z} (\bar{Z}'^2 - \bar{Z}^2 e^{2ik'_{mn,z}l})^{-1} (e^{2ik'_{mn,z}l} - 1) e^{2ik_{mn,z}h}, \\ E_{j,mn,\perp}^{0,f} &= E_{j,mn,\perp}^0 \bar{Z}' (\bar{Z}' - \bar{Z}) (\bar{Z}'^2 - \bar{Z}^2 e^{2ik'_{mn,z}l})^{-1} e^{i(k_{mn,z} - k'_{mn,z})h}, \\ E_{j,mn,\perp}^{0,g} &= E_{j,mn,\perp}^0 \bar{Z} (\bar{Z}' - \bar{Z}) (\bar{Z}'^2 - \bar{Z}^2 e^{2ik'_{mn,z}l})^{-1} e^{i((k_{mn,z} + k'_{mn,z})h + 2k'_{mn,z}l)}, \\ E_{j,mn,\perp}^{0,s} &= E_{j,mn,\perp}^0 (\bar{Z}'^2 - \bar{Z}^2) (\bar{Z}'^2 - \bar{Z}^2 e^{2ik'_{mn,z}l})^{-1} e^{i(k'_{mn,z} - k_{mn,z})l}. \end{aligned}$$

Tu gavaerTianeBT am or miRebul amonaxsnebs, maSin gvecodineba ra vel ebi iqmneba erTi harmonikis difraqciis dros diel eqtrikul fenaze da aqedan advil ad vipoviT j amur vel ebs. exl a ucnobia mxol od denis ampl itudebi mesris el ementSi da maT Sesabamis sasazRvro pirobidan vipoviT.

**damxmare gamomsxivebl ebis meTodiS gamoyeneba.** wina paragrafSi Cven amovxseniT difraqciis amocana im SemTxveviSTvis, rodesac meseri imyofeboda diel eqtrikul i fenis SigniT da gamoviyeneT amisaTvis damxmare gamomsxivebl ebis meTodi. es meTodi aseve SeiZl eba gamoyenebul iqnas am SemTxvevaSic, anu rodesac meseri imyofeba aRniSnul i fenis gareT. amisaTvis fenis zedapirebis maxl obl ad unda avagoT oTxi damxmare zedapiri da ganval agoT maTze damxmare gamomsxivebl ebi.

ganxil eba ori gare da ori Sida damxmare zedapirebi:

$$(x, y) \in (d_1 \times d_2), \quad z = -h + \delta, \quad z = -(h+d) - \delta, \quad z = -h - \delta, \quad z = -(h+d) + \delta,$$

sadac  $\delta$  warmoadgens manZil s damxmare zedapirsa da fenis zedapiris Soris. aseve rogorc wina TavSi, Cven aqac unda ganvixil oT ori urTierTmarTobul i el ementarul i wyaro, roml is vel sac gaaCnia saxe (3.1.2) – (3.1.3):

$$\begin{aligned} \vec{G}_E(\vec{r}, \vec{r}_\alpha) &= (1/2\omega\varepsilon_0\varepsilon d_1 d_2) \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} e^{i\vec{k}_{\alpha,mn}(\vec{r}-\vec{r}_\alpha)} (\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{k}_{\alpha,mn} (\vec{k}_{\alpha,mn} \cdot \vec{p}_\alpha) - \mu\varepsilon k^2 \vec{p}_\alpha), \\ \vec{G}_H(\vec{r}, \vec{r}_\alpha) &= (1/2d_1 d_2) \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} e^{i\vec{k}_{\alpha,mn}(\vec{r}-\vec{r}_\alpha)} (\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2)^{-1/2} (\vec{p}_\alpha \times \vec{k}_{\alpha,mn}), \end{aligned}$$

$$\vec{k}_{\alpha,mn} = \vec{k}_{\alpha,mn} \left\{ k_{n,x}, k_{m,y}, \text{sgn}(z - z_\alpha) \sqrt{\mu\varepsilon k^2 - k_{n,x}^2 - k_{m,y}^2} \right\}, \quad k_{n,x} = k_x + 2\pi n/d_1, \quad k_{m,y} = k_y + 2\pi m/d_2.$$

maTi orientacia unda ganisazRvrebodes Sesabamisad  $\vec{x}$  da  $\vec{y}$  bazisuri veqtorebiT. amasTanave, orive el ementarul wyaros damxmare

gamomsxivebel Si unda gaaCndes sakuTari ucnobi ampl itudebi. naTqvamis gaTval iswinebiT, vel ebisTvis (I) – (IV) areebSi davwerT:

(I). aq gagvaCnia dacemul i da mesridan zeviT mimaval i vel ebi:

$$\vec{E}_{inc}(\vec{r}) + \vec{E}_1(\vec{r}) = \vec{E}_0 e^{i\vec{k}\vec{r}} + \sum_{j=1}^N I_j \vec{G}_E(\vec{r}, \vec{r}_j), \quad \vec{H}_{inc}(\vec{r}) + \vec{H}_1(\vec{r}) = \vec{H}_0 e^{i\vec{k}\vec{r}} + \sum_{j=1}^N I_j \vec{G}_H(\vec{r}, \vec{r}_j),$$

$$z_j = 0, \quad \vec{p}_j = d\vec{l}_j, \quad z > dr_0, \quad \text{sgn}(z - z_j) = 1.$$

(II). gagvaCnia mesridan qveviT mimaval i vel i da aseve vel i romel ic  $z = -h - \delta$  damxmare zedapiriT aRiwereba:

$$\vec{E}_2(\vec{r}) + \vec{E}_e(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_E(\vec{r}, \vec{r}_j) + \sum_{\alpha=1}^Q \sum_{\alpha'=1}^P \left( A_{\alpha\alpha'} \vec{G}_E^x(\vec{r}, \vec{r}_{\alpha\alpha'}) + B_{\alpha\alpha'} \vec{G}_E^y(\vec{r}, \vec{r}_{\alpha\alpha'}) \right),$$

$$\vec{H}_2(\vec{r}) + \vec{H}_e(\vec{r}) = \sum_{j=1}^N I_j \vec{G}_H(\vec{r}, \vec{r}_j) + \sum_{\alpha=1}^Q \sum_{\alpha'=1}^P \left( A_{\alpha\alpha'} \vec{G}_H^x(\vec{r}, \vec{r}_{\alpha\alpha'}) + B_{\alpha\alpha'} \vec{G}_H^y(\vec{r}, \vec{r}_{\alpha\alpha'}) \right),$$

$$z_j = 0, \quad \vec{p}_j = d\vec{l}_j, \quad z_{\alpha\alpha'} = -h - \delta \quad -h < z < -dr_0, \quad \text{sgn}(z - z_j) = -1, \quad \text{sgn}(z - z_{\alpha\alpha'}) = 1.$$

aq  $\alpha\alpha'$  indeqsebi miuRiTeben damxmare gamomsxivebl is nomers da maSasadame TiToeul damxmare zedapirze maTi raodenobaa  $Q \times P$ .

(III). aq gagvaCnia  $z = -h + \delta$  da  $z = -(h+d) - \delta$  gare zedapirebis mier Seqmnil i vel ebi:

$$\vec{E}_f(\vec{r}) + \vec{E}_g(\vec{r}) = \sum_{\beta=1}^Q \sum_{\beta'=1}^P \left( C_{\beta\beta'} \vec{G}_E^x(\vec{r}, \vec{r}_{\beta\beta'}) + D_{\beta\beta'} \vec{G}_E^y(\vec{r}, \vec{r}_{\beta\beta'}) \right) +$$

$$+ \sum_{\gamma=1}^Q \sum_{\gamma'=1}^P \left( F_{\gamma\gamma'} \vec{G}_E^x(\vec{r}, \vec{r}_{\gamma\gamma'}) + L_{\gamma\gamma'} \vec{G}_E^y(\vec{r}, \vec{r}_{\gamma\gamma'}) \right),$$

$$\vec{H}_f(\vec{r}) + \vec{H}_g(\vec{r}) = \sum_{\beta=1}^Q \sum_{\beta'=1}^P \left( C_{\beta\beta'} \vec{G}_H^x(\vec{r}, \vec{r}_{\beta\beta'}) + D_{\beta\beta'} \vec{G}_H^y(\vec{r}, \vec{r}_{\beta\beta'}) \right) +$$

$$+ \sum_{\gamma=1}^Q \sum_{\gamma'=1}^P \left( F_{\gamma\gamma'} \vec{G}_H^x(\vec{r}, \vec{r}_{\gamma\gamma'}) + L_{\gamma\gamma'} \vec{G}_H^y(\vec{r}, \vec{r}_{\gamma\gamma'}) \right),$$

$$z_{\beta\beta'} = -h + \delta, \quad z_{\gamma\gamma'} = -(h+d) - \delta, \quad -(h+d) < z < -h, \quad \text{sgn}(z - z_{\beta\beta'}) = -1, \quad \text{sgn}(z - z_{\gamma\gamma'}) = 1.$$

(IV). aq mxol od  $z = -(h+d) + \delta$  damxmare zedapiridan qveviT mimaval i (gasul i) vel i gagvaCnia:

$$\vec{E}_s(\vec{r}) = \sum_{\sigma=1}^Q \sum_{\sigma'=1}^P \left( K_{\sigma\sigma'} \vec{G}_E^x(\vec{r}, \vec{r}_{\sigma\sigma'}) + R_{\sigma\sigma'} \vec{G}_E^y(\vec{r}, \vec{r}_{\sigma\sigma'}) \right),$$

$$\vec{H}_s(\vec{r}) = \sum_{\sigma=1}^Q \sum_{\sigma'=1}^P \left( K_{\sigma\sigma'} \vec{G}_H^x(\vec{r}, \vec{r}_{\sigma\sigma'}) + R_{\sigma\sigma'} \vec{G}_H^y(\vec{r}, \vec{r}_{\sigma\sigma'}) \right),$$

$$z_{\sigma\sigma'} = -(h+d) + \delta, \quad z < -(h+d), \quad \text{sgn}(z - z_{\sigma\sigma'}) = -1.$$

maSasadame, ucnobi vel ebi gamosaxul ia periodul i grinis funqciebiT romel nic imyofebian damxmare zedapirebze da aseve mesris el ementis gaswvri.

Cveni amocana kvl av dayvanil ia imaze rom vipovoT denis ucnobi  $I_j$  ampl itudebi ( $j=1,2,\dots,N$ ) da damxmare gamomsxivebl ebis ampl itudebi  $A_{\alpha\alpha'}$ ,  $B_{\alpha\alpha'}$ ,  $C_{\beta\beta'}$ ,  $D_{\beta\beta'}$ ,  $F_{\gamma\gamma'}$ ,  $L_{\gamma\gamma'}$ ,  $K_{\sigma\sigma'}$ ,  $R_{\sigma\sigma'}$ , sadac  $(\alpha, \beta, \gamma, \sigma = 1, 2, \dots, Q, \alpha', \beta', \gamma', \sigma' = 1, 2, \dots, P)$ . sul gagvaCnia  $8Q \times P + N$  ucnobi da isini (3.2.6), (3.2.7)

sasazRvro pirobedidan unda vipovoT. diel eqtrikis zedapirze moviTxovT sasazRvro pirobis Sestrul ebas  $Q \times P$  raodenobis gansxvavebul wertil Si. aseve viTxovT sasazRvro pirobis Sestrul ebas mesris el ementis  $N$  segmentze:

$$\left\{ \begin{array}{l} \left( \vec{E}_2(\vec{r}_{\varphi\varphi'}) + \vec{E}_e(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{x} = \left( \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{x} \\ \left( \vec{H}_2(\vec{r}_{\varphi\varphi'}) + \vec{H}_e(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{x} = \left( \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{x} \\ \left( \vec{E}_2(\vec{r}_{\varphi\varphi'}) + \vec{E}_e(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{y} = \left( \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{y} \\ \left( \vec{H}_2(\vec{r}_{\varphi\varphi'}) + \vec{H}_e(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{y} = \left( \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-h} \cdot \vec{y} \\ \left( \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{x} = \vec{E}_s(\vec{r}_{\varphi\varphi'}) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{x} \\ \left( \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{x} = \vec{H}_s(\vec{r}_{\varphi\varphi'}) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{x} \\ \left( \vec{E}_f(\vec{r}_{\varphi\varphi'}) + \vec{E}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{y} = \vec{E}_s(\vec{r}_{\varphi\varphi'}) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{y} \\ \left( \vec{H}_f(\vec{r}_{\varphi\varphi'}) + \vec{H}_g(\vec{r}_{\varphi\varphi'}) \right) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{y} = \vec{H}_s(\vec{r}_{\varphi\varphi'}) \Big|_{z_{\varphi\varphi'}=-(h+d)} \cdot \vec{y} \\ \left( \vec{E}_{inc}(\vec{r}_\sigma) + \vec{E}_1(\vec{r}_\sigma) + \vec{E}_e(\vec{r}_\sigma) \right) \cdot d\vec{l}_\sigma = 0 \end{array} \right.$$

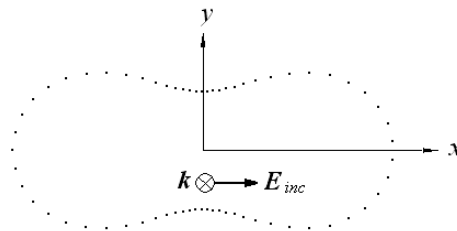
sadac  $\varphi=1,2,\dots,Q$ ,  $\varphi'=1,2,\dots,P$   $\sigma=1,2,\dots,N$ . am sistemis amoxsna kompiuterul i model irebit xdeba. amis Semdeg SegviZi ia vipovoT difraqciis Sedegad miRebul i vel i sivrcis nebismier wertil Si.

### §3.3 ricxviTi eqsperimentebis Sedegebi

**al goriTmis cdomil ebis dadgena.** sanam gadaval T konkretul i struqturebis gamokvl evaze Seqmnil i programul i paketis saSual ebIT, pirvel rigSi unda Semowmebul iqnas misi sizuste. es gul isxmobs damxmare parametrebis optimal uri mniSvel obebis dadgenas. rogorc I TavSi iyo naxsenebi, damxmare parametrebs warmoadgenen: 1. damxmare zedapirebis  $d/\lambda_0$  daSoreba diel eqtrikis real ur zedapiridan, 2. damxmare wyaroebis raodenoba tal Ris sigrZis kvadratis farTobze, 3. mesris el ementis mavTul is radiusi  $dr_0/\lambda$ , 4. el ementarul i segmentebis raodenoba tal Ris sigrZeze. aq  $\lambda_0$  da  $\lambda$ , Sesabamisad, warmoadgenen tal Ris sigrZes Tavisufal sivrcesi da diel eqtrikis SigniT. zustad am damxmare parametrebis mniSvel obebzea damokidebul i miRebul i Sedegebis samarTI ianoba. Cven vTvl iT, rom Sedegi aris samarTI iani, Tu srul i cdomil eba sasazRvro pirobebis Sestrul ebaSi ar aRemateba 15% rogorc diel eqtrikis zedapirze, aseve mesris gamtari el ementebis gaswvri. unda aRiniSnos, rom am SemTxvevaSi sasazRvro pirobebis Sestrul eba mowmdeba rogorc TviT kol okaciis wertil ebSi, aseve maT Sua wertil ebSi, sadac gadaxra am pirobebis Sestrul ebidan maqsimal uria. amastanave, ganxil ul SemTxvevaSi

unda srul debodes aseve kidev erTi aucil ebel i piroba: Tu diel eqtriks ar gaaCnia danakargebi, dacemul i vel is energia unda udrides arekvl il i da gasul i vel ebis energiebis jams  $W_{inc} = W_R + W_T$  - rasac energiis Senaxvis kanoni moiTxovs. Tu gaviTval iswinebT, rom energia aris vel is amplitudis kvadratis proporciul i, maSin SegviZl ia davwerOT  $E_{inc}^2 = E_R^2 + E_T^2$ , saidanac gamomdinareobs tol oba  $R+T=1$ , sadac  $R = E_R^2/E_{inc}^2$ ,  $T = E_T^2/E_{inc}^2$  - arekvl is da gasvl is koeficientebia.

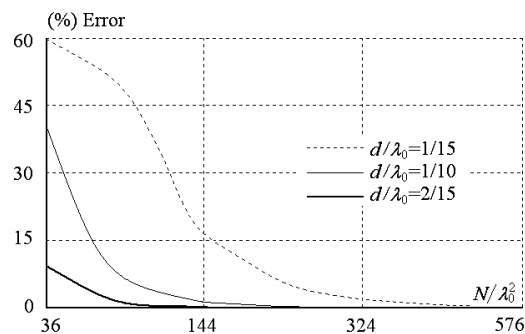
magal iTisTvis ganxil ul iqna SemTxveva, rodesac usasrul o orperiodul i meseri imyofeba brtyel i diel eqtrikul i fenis SigniT (nax. 3.1.1). mesris el ementi warmoadgens kasinis oval s (nax. 3.3.1). dacemul i brtyel i tal Ra OZ RerZis sawinaaRmdgo mimarTul ebiT vrcel deba da gaaCnia OX pol arizacia. diel eqtrikul i fenis sisqea  $l = (2/3)\lambda_0$ , SeRwevadobebia  $\varepsilon = 4$ ,  $\mu = 1$ , mesris periodebia  $d_1 = d_2 = (1/3)\lambda_0 = (2/3)\lambda$ .



$$\rho(\varphi) = \sqrt{c^2 \cos 2\varphi + \sqrt{a^4 - c^4 \sin^2 2\varphi}}, \varphi \in [0, 2\pi], a = 1.1c$$

nax. 3.3.1 kasinis oval i

Semdeg naxazze 3.3.2 moyvanil ia diel eqtrikze kol okaciis wertil ebs Soris sasazRvro pirobis Sesrul ebis cdomil ebis damokidebul eba wertil ebis raodenobaze.

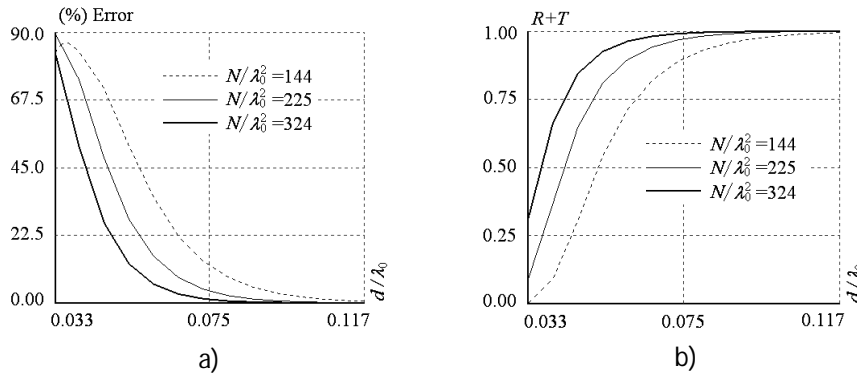


nax. 3.3.2 diel eqtrikze cdomil ebis damokidebul eba wertil ebis raodenobaze

damxmare zedapirebi aq arian daSorebul ebi real ur zedapiridan sxvadasxva manZil ebiT ( $d/\lambda_0 = 1/15, 1/10, 2/15$ ). rogorc vxedavT 36 kol okaciis wertil i tal Ris sigrZis kvadratis farTobze maRal cdomil ebas iZl eva, rodesac  $d/\lambda_0 = 1/15$ , Tumca maTi raodenobis gazrdiT cdomil eba mkveTrad mcirdeba da 324 wertil is SemTxvevaSi (18 wertil i

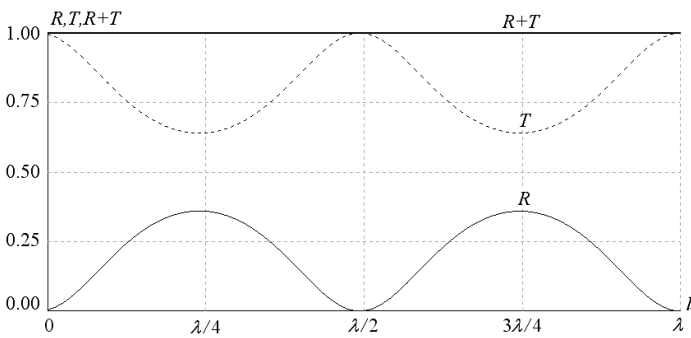
tal Ris sigrZeze) mas ukve dasaSvebi mniSvnel oba gaaCnia. meti daSoreba kidev ufro amcirebs cdomil ebas, magal iTad, Tu  $d/\lambda_0 = 2/15$  maSin cdomil eba 144 wertil is SemTxvevaSi (12 wertil i tal Ris sigrZeze) mxol od 2%-s Seadgens.

Semdeg moyvanil ia igive cdomil ebis damokidebul eba damxmare zedapirebis  $d$  daSorebaze diel eqtrikis zedapiridan (nax. 3.3.3 a)). daSorebas ganicdian rogorc Sida, aseve gare damxmare zedapirebi. aseve, paral el urad, moyvanil ia energiis bal ansis grafiki (nax. 3.3.3 b)).

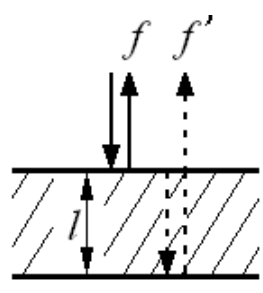


nax. 3.3.3 a) diel eqtrikze cdomil ebis da b) energiis bal ansis pirobis damokidebul eba damxmare zedapirebis daSorebaze

Semdeg naxazze moyvanil ia  $R$  arekvl is,  $T$  gasvl is koeficienebis da aseve maTi  $R+T$  j amis damokidebul eba diel eqtrikis  $l$  sisqeze (nax. 3.3.4). rogorc vxedaVT, arekvl is da gasvl is koeficientebi periodul ad icvl ebian. es aixsneba imiT, rom diel eqtrikis sisqis cvl il ebis dros, icvl eba fazaTa sxvaoba zeda zedapiridan arekvl il  $f$  vel sa da qveda zedapiridan arekvl il s da Semdeg gamosul  $f'$  vel ebs Soris (nax. 3.3.5).



nax. 3.3.4  $R$ ,  $T$  koeficientebis da maTi j amis damokidebul eba diel eqtrikis sisqeze



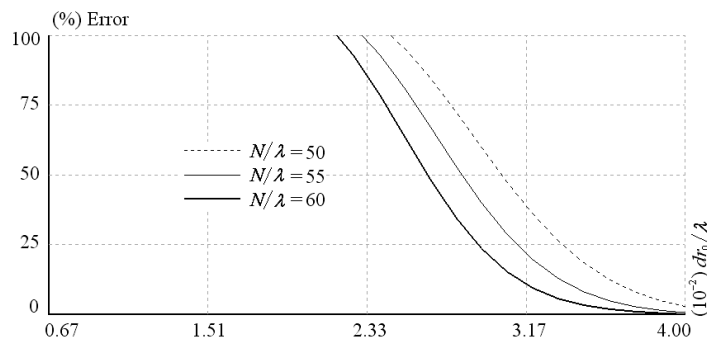
nax. 3.3.5  $f$  da  $f'$  vel ebi

amis Sedegad, zogierT SemTxvevaSi (arekvl is koeficientis maqsimumebi) adgil i aqvs maTi fazebis damTxvevas, rac, interferenciis Sedegad iwevs arekvl il i vel is gaZl ierebas. sxva SemTxvevaSi (arekvl is koeficientis minimebi)  $f$  da  $f'$  vel ebi sawinaaRmdego fazebiT xvdebian da faqturad axSoben erTmaneTs, rac Sesabamisad iwevs gasvl is koeficientis gazrDas. amitom grafikis periodul oba aris  $\lambda/2$ . nebismier SemTxvevaSi, arekvl is da gasvl is koeficientebis j ami erTis tol ia, rac TanxmobaSia energiis

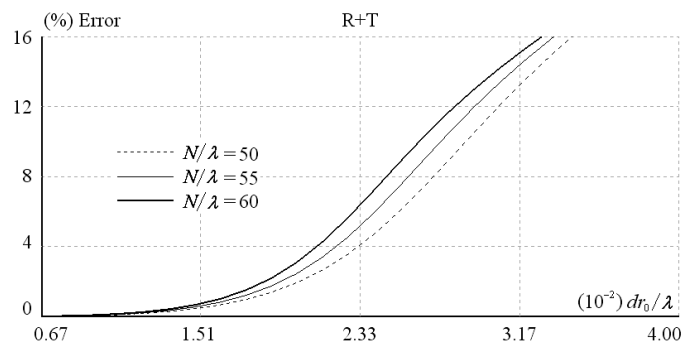


Senaxvis kanonTan. es miRebul i Sedegi aseve adasturebs kompiuterul i al gorITmis samarTI ianobas.

mesris el ementze cdomil ebis angariSis dros ganxil ul iqna rezonansul i SemTxveva, rodesac mesris el ementis srul i sigrZe faqtiurad tal Ris sigrZis tol ia diel eqtrikis SigniT ( $L=1.03\lambda$ ). gasagebia rom cdomil eba sxva (ararezonansul ) SemTxvevaSi miRebul ze mcire unda iyos. Catarebul ma kvl evebma gviCvena rom mavTul is radiusis gazrdiT mcirdeba sasazRvro pirobis Sestrul ebis cdomil eba, magram am SemTxvevaSi mcired irRveva  $R+T=1$  tol oba. naTqvami naTI ad Cans momdevno ori grafikidan, sadac moyvanil ia cdomil eba sasazRvro pirobisatvis da  $R+T=1$  tol obisatvis.



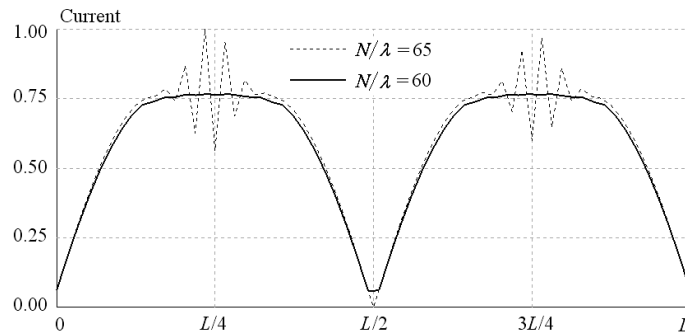
a)



b)

nax. 3.3.6 a) mesris el ementze sasazRvro pirobis da  
b) energiis bal ansis cdomil ebis  
damokidebul eba mavTul is radiusze

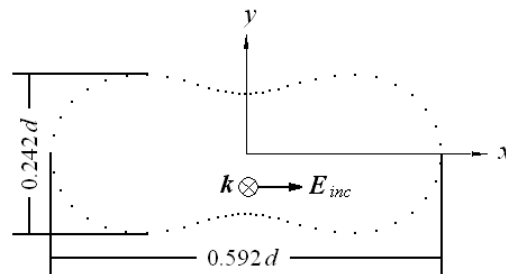
am suraTebze moyvanil ia sami grafiki, romel nic Seesabamebian mesris el ementze kol okaciis wertil ebis sxvadasxva raodenobas. rogorc vxedavT, cdomil eba orive SemTxvevaSi SedarebiT mcirdeba rodesac wertil ebis aRniSnul i raodenoba izrdeba, Tumca igi ar unda aRematebodes 60-s tal Ris sigrZeze, radgan winaaRmdeg SemTxvevaSi vRebul obT arafizikur denebis ganawil ebas el ementSi. es kargad Cans Semdeg suraTze, sadac moyvanil ia maqsimal ur mniSvnel obaze danormirebul i inducirebul i denis ganawil eba el ementSi (nax. 3.3.7).



nax. 3.3.7 danormirebul i inducirebul i denis ganawil eba mesris el ementSi

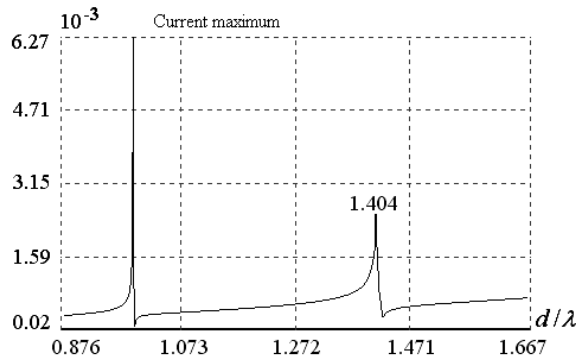
maSasadame, miRebul i mrudebis Tanaxmad, rezonansis SemTxvevaSi, fizikuri Sedegebis misaRebad saWiroa parametrebis Semdegi mniSvnel obebi:  $N/\lambda = 60$   $3.17 \cdot 10^{-2} < dr_0/\lambda < 4 \cdot 10^{-2}$ . unda aRiniSnos, rom mesris el ementebis dayofa tol monakveTebad zogad SemTxvevaSi kasinis el ementebisaTvis rTul deba da tal Ris sigrZeze el ementis gaswriw kol okaciis wertil ebis aseTi didi raodenoba nawil obriv amiT aixsneba.

**Tavisufal i sivrcis SemTxveva.** magal iTistTvis ganxil ul iqna kerZo SemTxveva, rodesac  $l = 2d$  sisqis brtyel i diel eqtrikul i fenis SeRwevadobebia  $\varepsilon = \mu = 1$ , rac Tavisufal sivrces Seesabameba. mesris periodebia  $d_1 = d_2 = d$ . damxmare zedapirebis daSoreba udris  $0.4d$ , xol o mavTul is sisqea  $0.02d$ . Semdeg suraTze moyvanil ia kasinis el ementis geometria da dacemul i vel is orientacia (nax. 3.3.8). mas gaaCnia erTeul ovani amplituda da  $Ox$  pol arizacia.



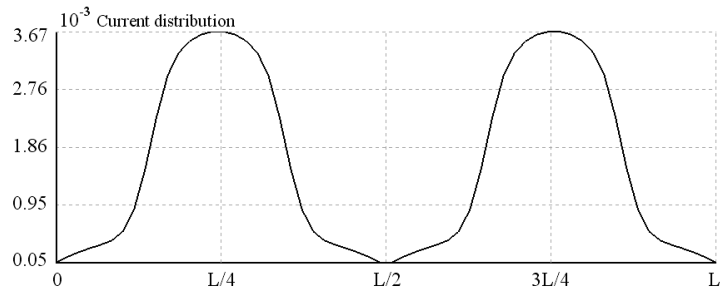
nax. 3.3.8 el ementis geometria da dacemul i tal Ris orientacia

dacemul i veil is tal Ris sigrZis cvl il ebiT Seswavi il ia el ementSi inducirebul i denis maqsimumis cvl il eba. naxazze 3.3.9 moyvanil diapazonSi, napovnia ganxil ul i sistemis parametrebis ori mniSvnel oba, rodesac el ementSi aRZrul dens maRal i mniSvnel oba gaaCnia:  $d/\lambda = 1$  da  $d/\lambda = 1.404$ . pirvel i maqsimumis mniSvnel oba warmoadgens mxol od mesris rezonanss. meore maqsimumis mniSvnel oba Seesabameba ormagi rezonansis SemTxvevas (rezonansia TviT el ementi da aseve rezonansul ia mesris periodi). rogorc vxedavT, aRZrul i deni rezonansebis SemTxvevaSi ori rigiT metia.

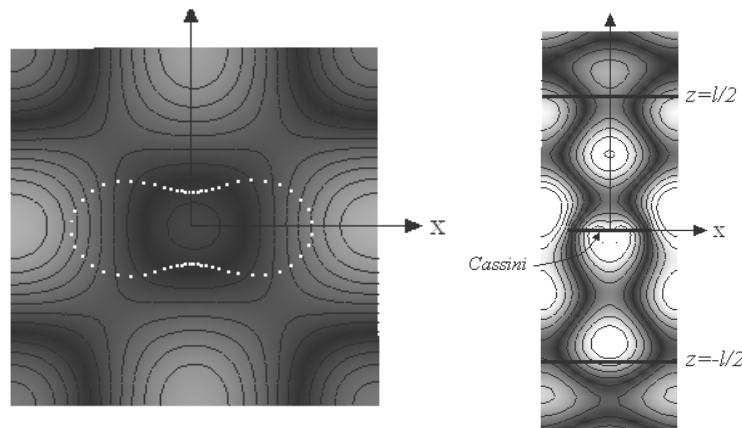


nax. 3.3.9 denis maqsimumi damoki debul eba dacemul i tal Ris sigrZeze

Semdeq suraTze (nax. 3.3.10) moyvanil ia denis ganawil eba mesris el ementSi rodesac  $d/\lambda = 1.404$ . rogorc vxedavT,  $Ox$  pol arizaciis SemTxvevaSi el ementis Cazneqil nawil Si ufro maRal i deni aRiZvReba.



nax. 3.3.10 denis ganawil eba el ementSi ormagi rezonansis dros



a) b)

nax. 3.3.11 axl o vel is ganawil eba a) mesris paral el ur da b) marTobul sibrtyeebSi

naxazze 3.3.11 moyvanil ia axl o vel is  $E_x$  komponentis ganawil eba mesris periodis fargl ebSi mis paral el ur da marTobul sibrtyeSi, ormagi rezonansis SemTxvevaSi, rodesac  $d/\lambda = 1.404$ . vel is daxatvis sibrtye a) suraTze imyofeba mesris sibrtyeidan  $0.3\lambda$  simaRI eze.

აჩვენებთ, რომ დიფერენციალური განტოლების  $z = \pm 1/2$  ველების კარგი მიახლოებაა როდესაც  $\varepsilon = 1$ .

### დასკვნა

ამოხსნის იყნა ბრტყელი ტალღის დიფრაქციის ამოცანის სისტემაში უსასრულო პერიოდული მესერი - ბრტყელი დიფერენციალური განტოლების იყნა შემთხვევები, როდესაც მესერი იმყოფება ფენის სიღრმეში და ასევე მის გარეშე. ეს ამოცანა პირველ შემთხვევაში ამოხსნის დამხმარე გამომსახველები მეთოდით, რომელიც პერიოდული გრინის ფუნქცია ასრულებს დამხმარე გამომსახველებს ისევე როგორც მეორე შემთხვევაში ამოხსნის მეთოდის გარეშე, განხილული იყნა ასევე ამოხსნის ორი მკაცრი მეთოდი. შემდეგ იყნა მოყვანილი რიცხვითი გამოთვლები შედეგები, სადაც პირველი რიგიდან დამხმარე პარამეტრების ოპტიმალური მნიშვნელობები. მაგალითისთვის განხილული იყნა კასინის ელემენტებისაგან შემდგარი მესერი.

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