**ABU RAYHON BERUNIY NOMIDAGI URGANCH DAVLAT UNIVERSITETI HUZURIDAGI ILMIY DARAJALAR BERUVCHI PhD.03/30.09.2020.FM.55.04 RAQAMLI ILMIY KENGASH**

**ION-PLAZMA VA LAZER TEXNOLOGIYALARI INSTITUTI**

**SHERMATOVA FERUZA ABDURASHID QIZI**

# YORUG‘LIK DIODLARI BILAN OPTIK DAMLANADIGAN NEODIMLI LAZERLAR

**01.04.11 – Lazer fizikasi**

**Fizika-matematika fanlari bo‘yicha falsafa doktori (PhD) dissertatsiyasi**
**AVTOREFERATI**

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**Contents of dissertation abstract of doctor of philosophy (PhD) on physical-mathematical sciences**

**Оглавление автореферата диссертации доктора философии (PhD) диссертации**

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**Fizika-matematika fanlari bo‘yicha falsafa doktori (PhD) dissertatsiyasi AVTOREFERATI**

Urganch - 2025

**Falsafa doktori (PhD) dissertatsiyasi mavzusi O'zbekiston Respublikasi Oliy ta'lim, fan va innovatsiyalar vazirligi huzuridagi Oliy attestatsiya komissiyasida B2024.3.PhD/FM1163 raqam bilan ro'yxatga olingan.**

Falsafa doktori dissertatsiyasi U.A.Arifov nomidagi Ion-plazma va lazer texnologiyalari institutida bajarilgan.

Dissertatsiya avtoreferati uch tilda (o'zbek, ingliz, rus (rezyume)) Ilmiy kengash veb-sahifasida (www.urdu.uz) hamda «Ziyonet» Axborot-ta'lim portalida (www.ziyonet.uz) joylashtirilgan.

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## KIRISH (falsafa doktori (PhD) dissertatsiyasining annotatsiyasi)

**Dissertatsiya mavzusining dolzarbligi va zarurati**. Jahonda hozirgi kunda kamxarajat va samarali lazerlarni ishlab chiqish lazer fizikasi sohasidagi asosiy vazifalardan boʻlib qolmoqda, bu oʻz navbatida yangi optik damlash manbalari va unga mos faol muhitlar boʻyicha uzluksiz tadqiqotlarni talab qiladi. Soʻnggi yillarda yorugʻlik diodlarini ishlab chiqarishda, ayniqsa ularning chiqish quvvati va xarakteristikalari barqarorligini taʼminlash borasida katta yutuqlarga erishilgan boʻlib, shu nuqati nazaridan yangi turdagi yorugʻlik diodlari bilan optik damlanadigan lazerlar yaratish jahon hamjamiyati diqqat markazida turibdi. Yorugʻlik diodlari optik damlash manbasi sifatida bir qator afzalliklarga, jumladan, elektr quvvatini optik energiyaga aylantirishda yuqori samaradorlik, arzon narx, ixcham tuzilish va uzoq xizmat muddati ega. Shu bois hozirgi vaqtda yorugʻlik diodlaridan lazer muhitiga energiya uzatishning samarali mexanizmlarini oʻrganish ayniqsa dolzarb masalaga aylanib, ushbu yo’nalishda nazariy va amaliy tadqiqotlarni amalga oshirish muhim hisoblanmoqda.

Jahonda soʻnggi yillarda – AQSh, Fransiya va Xitoydagi bir qancha ixtisoslashtirilgan ilmiy markazlarda yorugʻlik diodlari bilan optik damlashga mos keluvchi turli lazer faol muhitlarining xususiyatlarini oʻrganish, yorugʻlik diodlari bilan optik damlanadigan lazerlar samaradorligini oshirish maqsadida yangi yondashuvlar, jumladan, yorugʻlik diodlarini energiyasini faol muhitga yetkazishda maxsus optik materiallar – lyuminessensiya konsentratorlaridan foydalanish, yorugʻlik diodlari nurida ishlaydigan lazerlarning yangi konfiguratsiyalarini ishlab chiqish ustida tadqiqotlar olib borilmoqda. Ushbu yoʻnalishda yorugʻlik diodlarining energiyasini faol mihitga samarali yetkazish, yorugʻlik diodlari nurlanish spektriga mos yutilish xusuiyatlariga ega faol muhitlarni tadqiq qilish, lazer muhitidagi faol ionlar oʻrtasidagi oʻzaro energiya oʻtkazish mexanizmlari, jumladan lazer energetik sathlaridagi oʻtishlarni oʻrganish va tahlil qilish ustuvor yoʻnalishlardan hisoblanadi. Shu bilan birga yorugʻlik diodi nurlanishini lazer nuriga aylantirish bilan bogʻliq fizik jarayonlarni chuqur tadqiq qilish, yorugʻlik diodlari bilan optik damlanadigan lazerlar simulyatsion modellarini ishlab chiqish orqali samarali lazer konfiguratsiyalarini aniqlash, ularni optimallashtirish va amaliyotga tatbiq qilish dolzarb vazifalardan hisoblanmoqda.

Oʻzbekiston Respublikasida soʻnggi vaqtlarda energiyadan samarali foydalanishning yangi imkoniyatlarini oʻrganishga, ayniqsa, innovatsion energiya tejaydigan texnologiyalarini yaratish, energiyani konvertatsiya qilishning yangi imkoniyatlarini tadqiq qilish ilmiy masalalari bilan bir qatorda ilm-fan yutuqlariga asoslangan innovatsion faoliyatni davlat tomonidan qoʻllab-quvvatlash va ragʻbatlantirish boʻyicha tizimli chora-tadbirlar amalga oshirilmoqda. 2022-2026 yillarga moʻljallangan Oʻzbekiston Respublikasini innovatsion rivojlantirish strategiyasida, jumladan «... yangi turdagi mahsulotlar va innovatsion texnologiyalar yaratishning gʻoyadan yakuniy isteʼmolchigacha boʻlgan kompleks tizimini taʼminlash orqali innovatsiyalarga boʻlgan talabni ragʻbatlantirish»[1] vazifalari

[1] Oʻzbekiston Respublikasi Prezidentining Farmoni, 06.07.2022 yildagi PF-165-son

belgilab berilgan. Mazkur vazifalarni amalga oshirishda, jumladan, yangi turdagi energiya va narx jihatidan samarali boʻlishi kutilayotgan yorugʻlik diodlari bilan optik damlanadigan lazerlarni yaratish bilan bogʻliq fizik jarayonlarni tadqiq qilish, yorugʻlik diodi energiyasini toʻgʻridan-toʻgʻri lazer energiyasiga aylantirishda samaradorlikni oshirish uchun faol muhitlar va ularga mos sensibilizatorlarni aniqlash, yorugʻlik diodi bilan optik damlanadigan lazerlar prototiplarini yaratish uchun lazer simulyatsiya modellarini ishlab chiqish muhim masalalardan biri hisoblanadi.

Oʻzbekiston Respublikasi Prezidentining 2020-yil 29-oktabrdagi PF-6097-sonli "Ilm-fanni 2030-yilgacha rivojlantirish konsepsiyasini tasdiqlash toʻgʻrisida"gi[2], Oʻzbekiston Respublikasi Prezidentining 2022-yil 28-yanvardagi PF-60-sonli "2022 — 2026-yillarga moʻljallangan Yangi Oʻzbekistonning taraqqiyot strategiyasi toʻgʻrisida"gi[3] farmonlarida va mazkur ilmiy faoliyatga tegishli boshqa me'yoriy-huquqiy hujjatlarda belgilangan vazifalarni amalga oshirishga ushbu dissertatsiya tadqiqoti muayyan darajada xizmat qiladi.

**Tadqiqotning respublikadagi fan va texnologiyalari rivojlanishining ustuvor yoʻnalishlariga mosligi.** Ushbu ilmiy ish Oʻzbekiston Respublikasida ilmiy va texnologik rivojlanishning ustuvor yoʻnalishlariga, jumladan, PFI-2 "Energetika, energotejamkorlik va muqobil energiya manbalari: innovatsion energotejamkor texnika va texnologiyalar asosida energetika tarmogʻi samaradorligini oshirishning ilmiy muammolarini tadqiq etish"ga mos keladi.

**Muammoning oʻrganilganlik darajasi.** Mazkur mavzu boʻyicha bir qator muhim ilmiy tadqiqotlar turli xorijiy ilmiy markazlarda amalga oshirilgan, jumladan, lazer chiqish parametrlarini yaxshilash maqsadida yorugʻlik diodlari bilan optik damlanadigan turli lazer konfiguratsiyalarining samaradorliklari baholangan. Ushbu sohada muhim natijalar xorijlik olimlar, jumladan, AQSHdan (B.Villars, E.S.Hill, C.G.Durfee), Fransiyadan (A.Barbet, F.Balembois, F.Druon, P.Pichon, A.Paul, P.Georges va boshqalar), Koreyadan (K.Lee, H.C.Lee, J.Y.Cho, J.C.Lee, J.Yi), Xitoydan (J.Shen, S.Jiang, X.Huang, R.Jiang, P.Lu, S.Xu va boshqalar), Erondan (S.M.Zahedi, A.H.Farahbod, M.Mahmoudi) va boshqa tadqiqotchilar tomonidan qoʻlga kiritilgan.

Amerikalik olimlar Ce:Nd:YAG faol muhitidan foydalanib, koʻndalang optik damlash sxemasi yordamida maksimal 18 mJ lazer energiyasiga erishgan.

Fransuz olimlari tomonidan yorugʻlik diodlari bilan optik damlashning yangi konsepsiyasi – nurlanish chastotasi (toʻlqin uzunligi) oʻzgartiruvchilari sifatida lyuminessensiya konsentratorlaridan foydalanishni taklif qilingan. Bunday optik damlash sxemasining asosiy maqsadi yorugʻlik diodi nurlanishini maksimal darajada toʻplash va spektrning kengroq sohasini qamrab olish orqali fotonlarning yutilishini oshirishdir. Ushbu usul yordamida Ti:Sa, Nd:$YVO_4$, Cr:LiSAF kabi lazer kristallari oʻrganilgan.

J. Shen va hamkasblari eksperimental ravishda yorugʻlik diodi energiyasini Nd:YAG va Nd:shisha faol muhiti yordamida lazer nurlanish energiyasiga

[2] Oʻzbekiston Respublikasi Prezidentining Farmoni, 29.10.2020 yildagi PF-6097-son
[3] Oʻzbekiston Respublikasi Prezidentining Farmoni, 28.01.2022 yildagi PF-60-son

konvertatsiya qilishda yuqori optik samaradorlikka erishgan, bu koʻrsatkich mos ravishda 8% va 10.9% ni tashkil qilgan.

Biroq, yorugʻlik diodi bilan optik damlashda neodim ionlari kiritilgan ittriy asosidagi matritsalardan farqli boshqa kristall strukturalari, shuningdek, sensibilizator ionli neodim kristallarining salohiyati oʻrganilmaganligicha qolmoqda. Yorugʻlik diodi bilan optik damlanadigan lazerlardagi soʻnggi yutuqlarga qaramay, ushbu tizimlarda raqobatbardosh quvvat darajasiga yoki yetarli konversiya samaradorligiga erishilganligi toʻgʻrisida maʼlumot keltirilmagan. Buni oʻz navbatida yorugʻlik diodi energiyasini faol muhitga oʻtkazishning samarali mexanizmlarini toʻliq oʻrganilmaganligi va lazer tizimlarini ishlab chiqishda yorugʻlik diodi nurlanishining oʻziga xos xususiyatlarini yetarlicha hisobga olinmaganligi bilan izohlash mumkin.

**Dissertatsiya tadqiqotining dissertatsiya bajarilgan ilmiy-tadqiqot muassasasining ilmiy-tadqiqot ishlari rejalari bilan bogʻliqligi.** Dissertatsiya tadqiqoti Oʻzbekiston Respublikasi Fanlar Akademiyasi qoshidagi Ion-plazma va lazer texnologiyalari institutining davlat byudjeti mavzusi “Turli usullar bilan uygʻotiluvchi lazerlarning yangi materiallar va texnologiyalarni qoʻllash asosida samaradorligini oshirish mexanizmlarini tadqiq qilish” (2021-2024) doirasida amalga oshirilgan.

**Tadqiqot maqsadi** toʻgʻridan-toʻgʻri optik damlash sharoitida yorugʻlik diodi energiyasini lazer nurlanishiga aylantirish samaradorligini cheklovchi asosiy omillarni aniqlash va neodimli lazer kristallari asosida yuqori samarali lazer qurilmalarini ishlab chiqish boʻyicha yechimlarni taklif qilishdan iborat.

**Tadqiqot vazifalari:**

- yorugʻlik diodlarining simulyatsion modellarini ishlab chiqish;
- lazer chiqish xarakteristikalarini tahlili uchun yorugʻlik diodi yordamida optik damlanadigan lazerlar simulyatsion modellarini ishlab chiqish;
- yorugʻlik diod nurlanishining faol muhitga samarali energiya oʻtkazish mexanizmlarini tadqiq qilish;
- yorugʻlik diod yordamida optik damlanadigan lazerlarda yutilish samaradorligini oshirish maqsadida muqobil matritsali neodim ionlari qoʻshilgan kristallarni oʻrganish;
- yorugʻlik diod nurlanish spektridagi siljishning lazer chiqish xarakteristikalariga taʼsirini oʻrganish;
- yorugʻlik diod yordamida optik damlanadigan lazer tizimlarida $Ce^{3+}$ sensibilizator ionlari kiritilgan neodimli kristalli imkoniyatlarini oʻrganish.

**Tadqiqot obʼyekti:** yorugʻlik diodlari, qattiq jism holatidagi neodimli lazer faol muhitlari, sensibilizatorlar va turli xil lazer kvantroni konfiguratsiyalari.

**Tadqiqot predmeti:** fotonlarning lazer faol muhiti, sensibilizator bilan oʻzaro taʼsiri fizik jarayonlari, foton yutilishi, lyuminessensiya, sensibilizator ionlaridan faol ionlarga energiya uzatish va  yorugʻlik diodlari yordamida turli faol muhitlarni optik damlashda lazer nurlanishi jarayonlari.

**Tadqiqot usullari.** Dissertatsiya ishida lazer tizimlarida faol muhit va yorugʻlik diod nurlanishining spektral xususiyatlari hisobga olingan holda fizik jarayonlarni simulyatsiya qilishga asoslangan usullardan foydalanilgan.

Simulyatsiya modellari Monte-Karlo foton yo‘lini kuzatish usuli asosida ishlab chiqilgan.

**Tadqiqotning ilmiy yangiligi** quyidagilardan iborat:

yorug‘lik diodlarining nurlanish jarayonlarini modellashtirish uchun yorug‘lik diodi qurilmalarining texnik tavsifnomasidan to‘g‘ridan-to‘g‘ri fazoviy va spektral parametrlarini hisobga olish imkonini beruvchi yangi yondashuv taklif etilgan;

ilk bor yorug‘lik diodlari bilan optik damlanadigan lazerlarning simulyatsiya modellari Monte-Karlo foton yo‘lini kuzatish usuli asosida ishlab chiqilgan;

yorug‘lik diodi bilan optik damlanadigan lazer tizimlarida egrilangan sirtli lazer kvantronlarining tekis sirtli kvantronlarga qaraganda yutilish va energiya uzatish samaradorligi 5-6% yuqori ekanligi modellashtirish natijalari asosida aniqlangan;

yorug‘lik diodi bilan optik damlanadigan lazer tizimlarida Nd:KGW lazer sterjeni Nd:YAG ga nisbatan yuqori salohiyatga ega ekanligi aniqlangan;

yorug‘lik diod nurlanishining temperaturaga bog‘liq spektral siljishi lazer faol muhitining yutilish xususiyatlariga ta’sir qilishi, xususan, 3-5 nm ga spektral siljish natijasida yutilish samaradorligining 5% dan ko‘proq qiymatga kamayishi aniqlangan;

ko‘k yorug‘lik diodlari bilan ko‘ndalang optik damlangan Ce:Nd:YAG lazer tizimi asosida 10% optik samaradorlikka va 30 W dan ortiq lazer chiqish quvvatiga erishish mumkinligi simulyatsiya natijalari asosida aniqlangan.

**Tadqiqotning amaliy natijalari** quyidagilardan iborat:

yorug‘lik diodlarining nurlanish jarayonlarini modellashtirishda yangi yondashuv ishlab chiqilgan;

yorug‘lik diodlari bilan optik damlanadigan lazerlarning simulyatsiya modellari Monte-Karlo foton yo‘lini kuzatish usuli asosida ishlab chiqilgan;

yorug‘lik diodi bilan ko‘ndalang optik damlanadigan Nd:KGW lazer tizimlarida 31 W lazer chiqish quvvati va 10.3% optik samaradorlikka erishish mumkinligi asoslangan;

yorug‘lik diodi bilan ko‘ndalang optik damlanadigan Ce:Nd:YAG lazer tizimlarida 10% optik samaradorlik bilan 30 W dan ortiq lazer chiqish quvvatiga erishish imkoniyati asoslangan.

**Tadqiqot natijalarining ishonchliligi** fotonikadagi zamonaviy usullar va yondashuvlardan foydalanganlik bilan tasdiqlanadi. Xulosalar lazer muhitidagi asosiy jarayonlarning fizik mexanizmlari bo‘yicha fundamental nazariy tadqiqotlarga asoslangan va boshqa tadqiqotchilarning xulosalariga to‘liq mos keladi.

**Tadqiqot natijalarining ilmiy va amaliy ahamiyati.**

Tadqiqot natijalarining ilmiy ahamiyati yorug‘lik diodi bilan optik damlanadigan lazerlar uchun taklif etilgan faol muhitlari (Nd:KGW, Ce:Nd:YAG) va lazer kvantron konfiguratsiyalari yorug‘lik diodlari bilan optik damlanadigan lazerlar samaradorligini sezilarli darajada oshirish imkonini berishi, shuningdek, yorug‘lik diodi yordamida optik damlanadigan lazerlarning ishlab chiqilgan modellari nazariy tadqiqotlar uchun qo‘llanilishi mumkinligi bilan izohlanadi.

Tadqiqot natijalarining amaliy ahamiyati taklif etilgan ilmiy va texnik yechimlar yorug‘lik diodi energiyasini lazer energiyasiga aylantirish bilan bog‘liq yangi samarali texnologiyalarni ishlab chiqishda qo‘llanilishi mumkinligi bilan izohlanadi.

**Tadqiqot natijalarining joriy qilinishi.** Yorug‘lik diodi yordamida optik damlanadigan Nd:YAG, Ce:Nd:YAG va Nd:KGW lazer faol muhitlarida yutilish, issiqlik xususiyatlari va lazer nurlanish xarakteristikalarini o‘rganish bo‘yicha olingan natijalar quyidagi ilmiy-tadqiqot loyihalariga tatbiq etilgan:

uglerod nanotrubkalari kompyuter modelini yaratish uchun U.A. Arifov nomidagi Ion-plazma va lazer texnologiyalari institutida olib borilgan “Uglerodli nanostrukturalardan atomlarning sochilishi, adsorbsiyasi va inkapsulyatsiyasi jarayonlarini modellashtirish va sferik fullerenlardan elektronlarning elastik sochilishini nazariy tadqiq etish” byudjet mavzusidagi fundamental tadqiqotlarda foydalanilgan (O‘zbekiston Respublikasi Fanlar akademiyasining 2024 yil 17 dekabrdagi 2/1255-2798-sonli ma’lumotnomasi). Olingan natijalardan foydalanish uglerodli nanotrubkalarda atomlarning sochilishida temperatura ta’sirini baholash imkonini bergan;

ilk bor bir xil bo‘lmagan domen tuzilmali kristallarda uchinchi garmonik avlodni amalga oshirishda domenlar ketma-ketligini optimallashtirish uchun Monte-Karlo usuliga asoslanib ishlab chiqilgan algoritmlar Toshkent davlat texnika universitetida olib borilgan “Nochiziqli foton kristallarda femtosekund davomiylikdagi lazer impulslarining parametrik ta’siri natijasida – ko‘p rangli o‘ta qisqa lazer impulslarining manbaini olish usullarini yaratish” mavzusidagi Uzb-Ind-2021-96 loyihasida foydalanilgan (Toshkent davlat texnika universitetining 2024-yil 11-oktabrdagi 01/9-14-1717-sonli ma’lumotnomasi). Natijalarning qo‘llanilishi chiziqli bo‘lmagan fotonik kristallarda qisqa lazer impulslarini parametrik kuchaytirish bo‘yicha muhim ma’lumotlarni taqdim etgan bo‘lib, bu o‘z navbatida innovatsion optimallashtirish usullarini ishlab chiqish imkonini bergan.

**Tadqiqot natijalarining aprobatsiyasi.** Mazkur tadqiqot natijalari 8 ta xalqaro va respublika miqyosidagi ilmiy-amaliy konferensiyalarda muhokamadan o‘tkazilgan.

**Tadqiqot natijalarining e’lon qilinganligi.** Natijalar 14 ta ilmiy nashrda, jumladan, O‘zbekiston Respublikasi Oliy attestatsiya komissiyasi tomonidan dissertatsiya asosiy natijalarini chop etish uchun tavsiya etilgan jurnallarda 5 ta maqola chop etilgan va 1 ta dasturiy mahsulot ro‘yxatga olingan.

**Dissertatsiyaning tuzilishi va hajmi.** Dissertatsiya kirish, to‘rt bob, xulosa, adabiyotlar ro‘yxati va ilovalardan iborat bo‘lib, jumladan, 43 ta rasm va 6 ta jadvalni o‘z ichiga oladi. Asosiy matn 104 sahifada keltirilgan.

## DISSERTATSIYANING ASOSIY MAZMUNI

Dissertatsiyaning **kirish** qismida tadqiqot mavzusining dolzarbligi va ahamiyati asoslangan, tadqiqotning maqsad va vazifalari shakllantirilgan, tadqiqot ob'yekti, predmeti va metodlari, shuningdek dissertatsiya tadqiqotining respublikada fan va texnologiyalarni rivojlantirishning ustuvor yo'nalishlari bilan muvofiqligi keltirilgan. Tadqiqotning ilmiy yangiligi bayon qilingan, olingan natijalarning ishonchliligi asoslangan, ularning nazariy va amaliy ahamiyati ochib berilgan, natijalarning joriy etilishi, aprobatsiyasi, shuningdek dissertatsiya hajmi va tuzilishi to'g'risidagi ma'lumotlar keltirilgan.

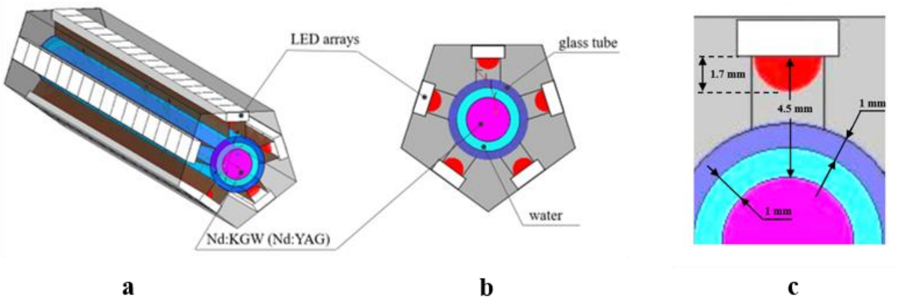
Dissertatsiyaning **"Yorug'lik diodi bilan optik damlanadigan lazerlarning hozirgi holati"** deb nomlangan **birinchi bobida** yorug'lik diodi bilan optik damlashning joriy holati to'g'risidagi adabiyotlar tahlili, shuningdek, yorug'lik diodlarning optik damlash jarayoniga bevosita ta'sir qiluvchi asosiy parametrlari va xususiyatlariga qisqacha tavsif berilgan. Adabiyotlar tahlili shuni ko'rsatadiki, so'nggi to'rt o'n yillikda yorug'lik diodlarining uzluksiz quvvati sezilarli darajada yaxshilanib, ikki-uch darajaga ko'tarilgan. Biroq shunga qaramay, yorug'lik diodi yordamida optik damlash quvvati odatda o'nlab kW/sm² diapazonida nurlanishga erishadigan lazer diodlaridan orqada qolmoqda.

Yorug'lik diodi bilan optik damlash ustida izlanayotgan laboratoriyalar soni kam bo'lgani sababli yorug'lik diodiga asoslangan optik damlash nisbatan tor ixtisoslik sohasi bo'lib qolmoqda. Bunday tor qamrov ushbu sohada tadqiqot olib borish imkoniyatlari bilan bir qatorda kengaytirilgan izlanishlar zaruratini ham ta'kidlaydi. Yorug'lik diodlarining lambertian nurlanish manbalari bo'lganligi sababli energiyani qattiq jism faol muhitga samaraliroq uzatishda ko'ndalang optik damlash sxemalari afzalroq hisoblanadi. Optik damlashda yuqori darajadagi chiqish quvvatiga erishish uchun yorug'lik diodlari asosan impuls (kvazi-uzluksiz) rejimida qo'llanilmoqda. Bunday rejim optik manba nurlanish quvvatini qisqa vaqt oralig'ida sezilarli darajada oshirish imkonini beradi va shu bilan birga lazer sterjenidagi qizish muammolarini kamaytirishga yordam beradi. Biroq, bu shuningdek, yorug'lik diodi nurlanishining spektral siljishiga olib kelishi mumkin bo'lib, bu esa o'z navbatida yorug'likning faol muhitda yutilish xususiyatlariga ta'sir qilishi mumkin.

Yuqoridagi fikrlarni inobatga olgan holda shuni xulosa qilish mumkinki, yorug'lik diodiga asoslangan optik damlash lazerlarini ishlab chiqish hali ham dastlabki rivojlanish bosqichida bo'lib, innovatsion yechim talab qilinadigan bir qator muammolar mavjud. Yorug'lik diodiga asoslangan damlash lazerlarining hozirgi holatini tahlil qilish asosida dissertatsiya ishining asosiy vazifalari belgilangan.

**Ikkinchi bob "Yorug'lik diodi bilan optik damlanadigan lazerlarda fizik jarayonlarni modellashtirish"** deb nomlanib, yorug'lik diodi bilan optik damlanadigan lazer modellarini MATLAB®, dasturlash va raqamli hisoblash platformasida Monte-Karlo fotonlarini kuzatish usuli yordamida ishlab chiqish jarayoniga bag'ishlangan. Yorug'lik diodlari nurlanishini modellashtirish jarayonida ularning spektral va fazoviy xususiyatlarini texnik tavsifidan to'g'ridan-to'g'ri hisobga olish imkonini beruvchi yangi usul taklif qilingan. Ushbu usul qurilmalardagi ikkilamchi optik elementlaridagi jarayonlarni modellashtirish zaruratini bartaraf qilinishi evaziga simulyatsiya jarayonini yengillashtirilishi bilan bir qatorda yuqori aniqlikni ham ta’minlaydi. Shuningdek, tanlangan modellashtirish usuli doirasida yorug‘lik diodlaridan chiqqan fotonlarning moddalar bilan o‘zaro ta’siri – optik damlash, yorug‘lik yutilishi, qaytishi, sinishi va hokazo optik jarayonlarda ko‘rib chiqilgan. Yorug‘lik diodlari bilan optik damlashda tanlangan modellashtirish usulining afzalliklari va kamchiliklari muhokama qilingan: Monte-Karlo fotonlarni kuzatish usuli yorug‘lik diodlari kabi murakkab yorug‘lik manbalari nurlanishi bilan bog‘liq fizik jarayonlarini modellashtirishga yaxshi mos keladi. Shuningdek, ushbu bobda yorug‘lik diodi yordamida optik damlangan lazerlarning chiqish quvvatini hisoblashda qo‘llanilgan fazoga bog‘liq tezlik tenglamalari keltirilgan. Ushbu tenglamalar tanlovi lazer kristallar ichida yorug‘lik diodlari nurlanishi yutilishining notekis taqsimoti bilan asoslanadi.

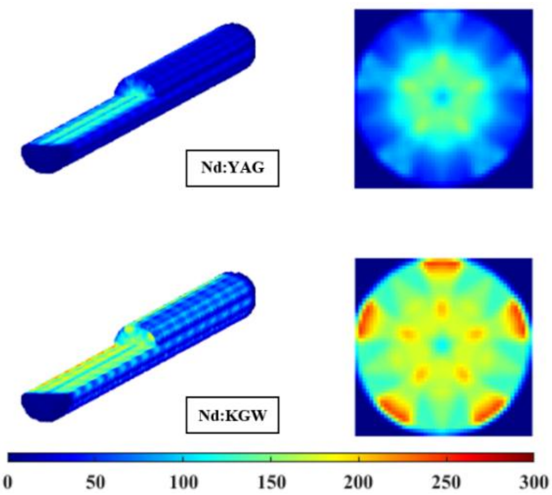
**Uchinchi “Yorug‘lik diodi yordamida optik damlanadigan Nd:YAG va Nd:KGW lazerlar” bob**da yorug‘lik diodi yordamida optik damlanadigan Nd:KGW lazeri uchun simulyatsiya usuli orqali olingan tadqiqot natijalari keltirilgan. Hozirgi kungacha ma’lum yorug‘lik diodi yordamida optik damlash orqali lazer nurlanishini olish bo‘yicha eksperimental ishlarning aksariyat qismi qismi Nd:YAG kristalida amalga oshirilgan. Neodim ionlarining boshqa host-matritsalar bilan yorug‘lik diodi yordamida optik damlash istiqbollari hali yetarlicha o‘rganilmagan. Neodim uchun alternativ host-matritsalardan biri KGW (kaliy-gadoliniy-volframat) bo‘lib, ushbu kristall struktura asosidagi faol muhit yorug‘lik diodlari bilan optik damlashda keng o‘rganilgan Nd:YAG va Nd:$YVO_4$ kabi lazer kristallariga nisbatan yuqori nurlanish ko‘ndalang kesimiga ega va 808 nm to‘lqin uzunligida keng yutilish sohasi mavjudligi bilan ajralib turadi.




**1-rasm.** Optik damlash kamerasining umumiy (a) va ko‘ndalang (b) ko‘rinishlari texnik parametrlari bilan birga (c).

Nd:KGWning yorug‘lik diodi bilan optik damlashning potensialini to‘liq baholash maqsadida Nd:KGW va Nd:YAG lazerlari bo‘yicha qiyosiy tadqiqot o‘tkazilgan. Ushbu tadqiqotda, Nd:KGW va Nd:YAG lazerlari bir xil optik damlash sharoitlarini ta’minlash uchun yaqinda eksperimental tadqiqotda Nd:YAG lazerini yorug‘lik diodi bilan optik damlashda foydalanilgan “besh yo‘nalishli optik damlash moduli” kvantroni asosida lazer simulyatsiya modellari ishlab chiqildi (1-rasm).

Simulyatsiya modelidan olingan ma’lumotlar asosida Nd:KGW ning yutilish samaradorligi Nd:YAG dan sezilarli darajada yuqori ekanligi aniqlandi. 2-rasmda keltirilgan yutilish taqsimotlari va rangli ustun optik damlash samaradorligini, yutilgan quvvat taqsimotining bir jinsli yoki emasligini vizual baholash imkonini

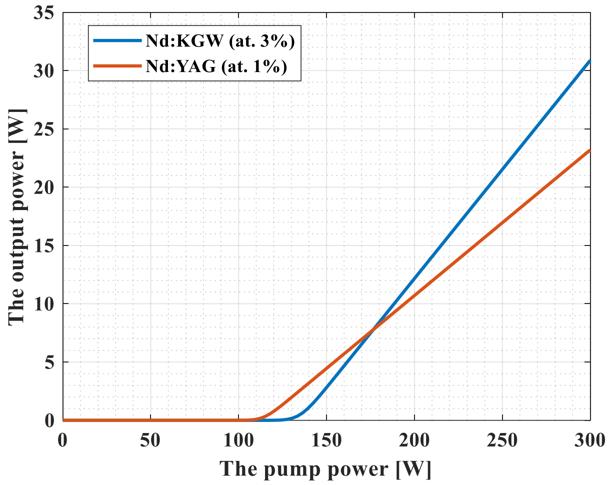



**2-rasm.** Yutilish taqsimotlari.

beradi. Ushbu taqsimotlar har bir yorug‘lik diodidan chiqarilgan 10 million foton statistikasi asosida hisoblangan, va rangli ustundagi qiymatlar har bir hajmiy birlikda yutilgan fotonlar soniga mos keladi (lazer kristalli x, y va z o‘qlari bo‘ylab 50×50×200 birlik elementiga bo‘lingan).

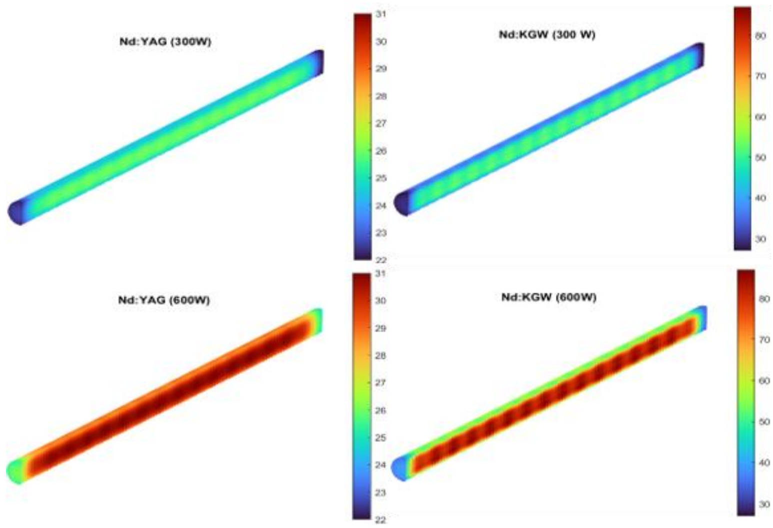
Umuman olganda, Nd:KGW dagi faol neodim ionlari yuqori konsentratsiyasi va yorug‘lik diodlari nurlanishi va Nd:KGW ning yutilish spektri bilan ko‘proq mos kelishi sababli bu natijalar namoyon bo‘lishi kutilgan edi. Modellashtirish yordamida baholangan yutilish samaradorligi yutilgan fotonlar foizidan kelib chiqqan holda Nd:KGW (66.2%) ning Nd:YAG (37.1%) dan ustunligini ko‘rsatdi (host-matritsalardagi neodim ionlari konsentratsiyasi mos ravishda 3% va 1% bo‘lganda). Undan keyin 3% Nd:KGW va 1% Nd:YAG lazerlarining chiqish parametrlarining qiyosiy tahlili o‘tkazildi (3-rasm).

Nd:KGW yuqori yutilish samaradorligi tufayli Nd:YAG ni ortda qoldirib, yuqori differensial samaradorlikni ko‘rsatdi (mos ravishda 17.9% va 12.1%). Nd:KGW xususiyatlariga, xususan, qisqaroq fluoressensiya vaqti va past kvant samaradorligiga mos ravishda, uning bo‘sag‘a quvvati yuqoriroq chiqqan, ammo bu qiymat Nd:YAG ga yaqin bo‘lib qolmoqda, bu esa Nd:KGW asosida yorug‘lik diodi yordamida optik damlanadigan yuqori quvvatli lazer yaratish imkoniyatini ko‘rsatadi.




**3-rasm.** Chiqish va kirish quvvati bog‘liqliklari (Nd:KGW vs Nd:YAG).

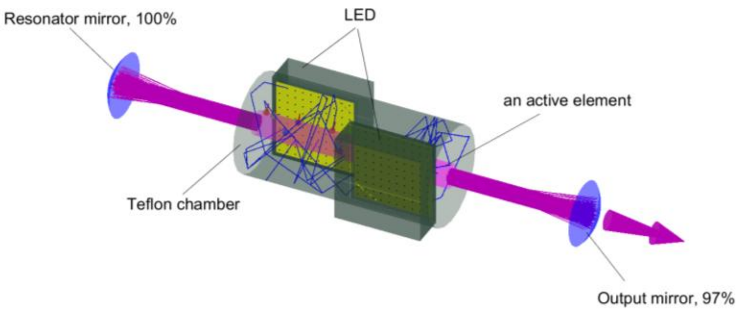
Ta’kidlash lozimki, keltirilgan chiqish quvvat-kirish quvvati bog‘liqliklari (3-rasm) lazer tizimlari uchun optimal sovutish sharoitlari farazida olingan. Amalda, ilmiy adabiyotlarda qayd etilishicha, KGW matritsasining past issiqlik o‘tkazuvchanligi va anizotropik xususiyatlari lazer qurilmalarida barqaror ish faoliyatini va yuqori samaradorlikni ta’minlash uchun samarali issiqlik tarqatish talab etiladigan holatlarda jiddiy muammo hisoblanadi. Yorug‘lik diodi yordamida optik damlanadigan lazer tizimlarida faol muhitda issiqlik to‘planishi termik linzalanishga olib kelishi mumkin, bunda temperatura gradiyenti kristallda sinish ko‘rsatkichining o‘zgarishiga sabab bo‘ladi. Bu hodisa chiqishdagi lazer dastasiga ta’sir qilishi va umumiy tizim samaradorligini pasaytirishi mumkin. Boshqa optik manbalar yordamida optik damlangan Nd:KGW lazerni o‘rganish bo‘yicha dastlabki tadqiqotlarda ushbu kristalldan foydalanishdagi asosiy cheklov sifatida aynan termal effektlar ko‘rsatilgan. Shu o‘rinda muhim savol tug‘iladi: yorug‘lik diodi yordamida optik damlashda olingan chiqish quvvati natijalariga termal yuklanish hisobi sezilarli ta’sir qiladimi? Buni o‘rganish uchun birinchi qadam sifatida Nd:YAG va Nd:KGW lazer sterjenlarining tegishli fizik xususiyatlari va simulyatsion model natijalari inobatga olingan holda faol muhitlarning turli optik damlash quvvatlaridagi temperatura taqsimoti issiqlik o‘tkazuvchanlik tenglamasi asosida hisoblab chiqildi (4-rasm).




**4-rasm.** Temperatura taqsimoti.

Nd:YAG da 300 va 600W optik damlash quvvatlarida minimal qizish kuzatildi va kristall markazi va chetki qismlari orasidagi temperatura farqi 5 darajadan yuqori bo‘lmasligi aniqlandi. Aksincha, Nd: KGW lazer muhitida sezilarli o‘zgarish kuzatilgan, 600 W yuqori quvvatida temperaturaning 90 darajaga ko‘tarilishi bilan bir qatorda taxminan 30 darajali temperatura gradiyenti (markaz va chekka qismlar o‘rtasidagi farq) kuzatilgan. Sovutish suyuqligining oqim tezligini oshirish, ayniqsa foydalanilgan ko‘ndalang optik damlash sxemasi bu gradiyentni kamaytirishi mumkin. Bundan tashqari, bugungi kunda yorug‘lik diodi yordamida optik damlanadigan lazerlar ko‘pchiligida yorug‘lik diodlari optik quvvatini oshirish uchun mo‘ljallangan impulsli optik damlash (kvazi-uzluksiz optik damlash rejimi) dan foydalaniladi, bu esa faol muhitdagi issiqlik muammolarini birmuncha kamaytiradi. Shuning uchun, ilgari qo‘yilgan savolga javoban, termal omillar 3-rasmda keltirilgan yorug‘lik diodi yordamida optik damlash tizimlarida Nd:KGW ning Nd:YAG ga nisbatan ustunligini namoyish qiluvchi natijalarga ta’sir qilmasligi kerak.

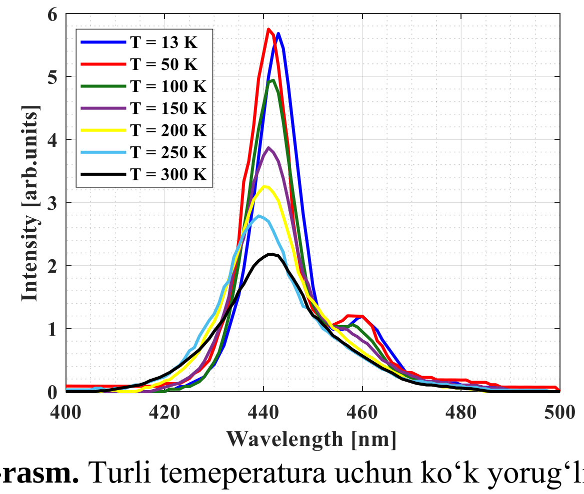
Dissertatsiyaning **“Yorug‘lik diodi bilan optik damlanadigan Ce:Nd:YAG lazeri simulyatsion modeli”** nomli **to‘rtinchi bobida** yorug‘lik diodi nurlanish energiyasini faol muhitga samarali tarzda o‘tkazish mexanizmlari yangi taklif etilgan tekis sirtli va egrilangan sirtli lazer kvantronlari parametrlarini optimallashtirish asosida ko‘rib chiqilgan. Shuningdek, yorug‘lik diodi bilan nurlantirilgan lazer tizimlari uchun sensibilizator ionlari qo‘shilgan neodim kristallari imkoniyatlari Ce:Nd:YAG misolida o‘rganilgan. Bundan tashqari, bu bobda yorug‘lik diodi nurlanishining temperaturaga bog‘liq spektral siljishining faol muhitning yutilish xususiyatlariga ta’siri simulyatsion usullar yordamida o‘rganilgan.




**5-rasm.** Modellashtirilgan Ce:Nd:YAG lazer tizimining umumiy ko‘rinishi.

Ce:Nd:YAG lazer kristallining yorug‘lik diodi yordamida optik damlashdagi imkoniyatlari avvalgi bir nechta eksperimental tadqiqotlarda ko‘rib chiqilgan. Boshlang‘ich nuqta sifatida ushbu tadqiqotlardan birini qo‘llash orqali Ce:Nd:YAG lazer tizimining dastlabki simulyatsion modeli ishlab chiqilgan (5-rasm). Ushbu eksperimental tadqiqotda turli diametrli (3 mm va 6 mm) Ce:Nd:YAG lazer sterjenlarida lazer chiqish parametrlari ko‘ndalang optik damlash sxemasida taqqoslangan: 12.8%li maksimal differensial samaradorlik 6 mm diametrli Ce:Nd:YAG lazer sterjenida erishilgan.

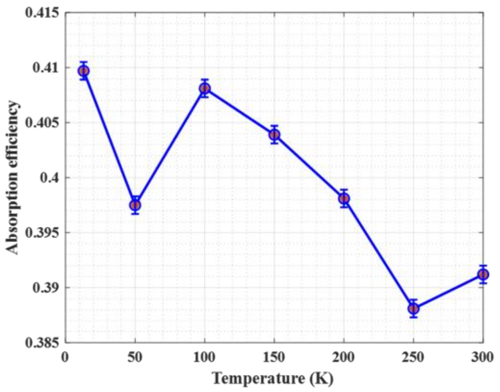
Yorug‘lik diodlari texnologiyalaridagi sezilarli yutuqlarga qaramay, ularning past chiqish quvvati yorug‘lik diodi yordamida optik damlanadigan lazerlarni ishlab chiqishda jiddiy muammo bo‘lib qolmoqda. Texnik jihatdan, yorug‘lik diodini ma’lum vaqt intervalida ishga tushirish, ya’ni kvaz-iuzluksiz (QCW) deb nomlanuvchi optik damlash rejimini kiritish orqali lazer tizimlarida bo‘sag‘a quvvatiga yetarli yuqori chiqish quvvatiga erishish mumkin. Biroq uzluksiz (CW) rejim bilan solishtirganda, QCW rejimi qo‘shimcha muammolarni keltirib chiqaradi, masalan, yuqori tok oqimi va kuchlanishlar yorug‘lik diodidagi temperaturaning ko‘tarilishiga sabab bo‘ladi. Ushbu temperaturaviy ta’sirlar optik damlash manbai nurlanishining spektral siljishiga olib kelishi mumkin. Spektral siljish o‘z navbatida yorug‘lik diodi nurlanish spektri va faol muhitning yutilish spektri o‘rtasidagi ustma-ust tushuvchanlikni o‘zgartirishi mumkin. Shu sababli, dissertatsiya doirasida yorug‘lik diodi nurlanishi spektral siljishining lazer nurining chiqish xususiyatlariga ta’sirini o‘rganish vazifasi qo‘yilgan edi. Bundan tashqari spektral siljishning ta’sirini o‘rganish uchun turli temperaturada o‘lchangan ko‘k yorug‘lik diodi nurlanish spektrlari o‘rganilgan eksperimental ish natijalaridan foydalanilgan. Ushbu nurlanish spektrlari raqamli ravishda qayta ishlanib (6-rasm), yorug‘lik diodi bilan optik damlanadigan lazerning validatsiyalagan simulyatsion modeli (5-rasm)ga kiritildi. Optik damlash xususiyatlarini asosan ikki asosiy parametr bilan baholash mumkin: optik damlash samaradorligi va yutilish taqsimoti. Bu omillar lazerning samaradorligiga sezilarli ta’sir ko‘rsatadi. Dastlab simulyatsion model yordamida yorug‘lik diodi nurlanishining



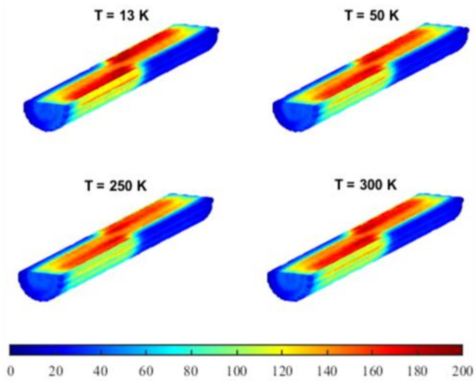

**6-rasm.** Turli temeperatura uchun ko‘k yorug‘lik diodlarining raqamli qayta ishlangan eksperimental nurlanish spektrlari.

spektral siljishi qayd qilingan har bir temperatura ko‘rsatkichi uchun bir xil optik damlash sharoitlarida va bir xil foton statistikasida optik damlash samaradorliklari aniqlandi.

Yorug‘lik diodidagi turli temperaturalar tufayli yuzaga keladigan optik damlash (yutilish) samaradorliklari orasidagi maksimal tafovut T=13 K va T=250 K uchun 5.4% ni tashkil etdi. Qolgan 13–300 K temperatura oralig‘i uchun modellashtirish natijalariga asoslanib hisoblangan fotonlarning yutilish samaradorligi 0.388–0.41 sohasida bo‘ldi (7-rasm). Keyin har bir temperatura uchun yorug‘lik diodi nurlanishining eksperimental olingan optik spektrlari asosida yutilish taqsimotlari aniqlandi. 8-rasmda to‘rtta qayd qilingan temperatura ko‘rsatkichi uchun yutilish taqsimotlarining umumiy ko‘rinishi va o‘zgarish darajasi keltirilgan. Past temperaturalarda faol muhitda yutilishning aniqroq sohalari kuzatilganini ta’kidlash mumkin. Lazer kristalli ichidagi umumiy yutilish sohalari o‘zgarmagan bo‘lsa-da, yorug‘lik diodining ishchi temperaturasi oshishi bilan yutilish xususiyatlarining sezilarli susayib borish qonuniyatlari kuzatilgan.

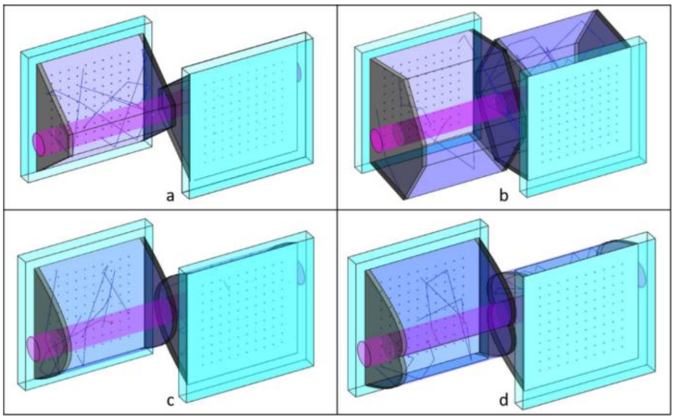



**7-rasm.** Yutilish samaradorligining yorug‘lik diodidagi temperaturaga bog‘liqligi.



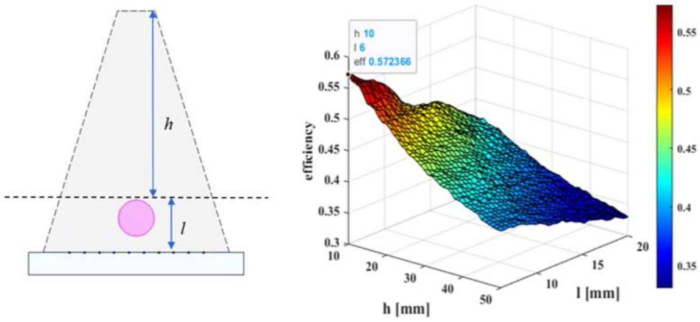

**8-rasm.** Yorug‘lik diodining 13-300 K ishchi temperaturasi oralig‘i uchun faol muhitda foton yutilishining taqsimoti.

Simulyatsiya modeli va eksperimental natijalar orasidagi muvofiqlikka erishilgandan so‘ng, Ce:Nd:YAG asosidagi lazer tizimini optimallashtirish lazer kvantroni konstruksiyalarini o‘zgartirish orqali amalga oshirildi. Lazer kvantronining to‘rt xil turi uchun simulyatsiya modellari ishlab chiqildi: trapezoidal ko‘p qirralik, geksagonal ko‘p qirralik, parabolik silindr va qo‘shaloq parabolik silindr (9-rasm).



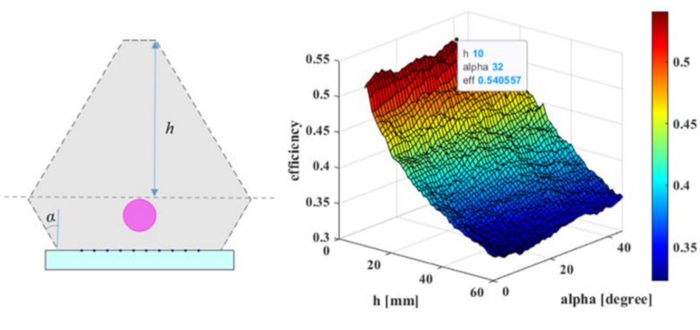

**9-rasm.** Taklif qilinayotgan lazer kvantronlarining umumiy ko‘rinishi: a) trapezoidal ko‘p qirralik; b) geksagonal ko‘p qirralik; c) parabolik silindr; d) qo‘shaloq parabolik silindr.

Yutilishning nisbatan bir jinsli taqsimotiga erishish maqsadida, ko‘rib chiqilgan eksperimental ishda lazer sterjeni optik o‘qi bo‘ylab qarama-qarshi tomonlarga joylashtirilgan ikkita yorug‘lik diodi ishlatilgan. Ushbu yondashuvga amal qilgan holda, lazer kvantronining yangi konstruksiyalarini modellashtirish jarayonida har bir konfiguratsiyani ikkita bir xil yorug'lik diodidan iborat blok va bitta lazer sterjenidan iborat bir butun tizim sifatida ko'rib chiqildi: sterjen diametri 5 mm, har bir blok uzunligi 25 mm. Ikki blokli tizimning umumiy uzunligi 50 mm tashkil etadi. Lazer kvantronining tahlilini soddalashtirish uchun dastlab har bir taklif qilinayotgan konfiguratsiyada faqat bitta blokni optimallashtirish natijasida yutilish samaradorligini maksimal oshirish nuqtai nazaridan o'rganib chiqildi. Bunda har bir konfiguratsiya uchun ikkita asosiy parameter tanlab olinib, ularning real amalga oshirilishi mumkin bo'lgan parametrlari sohasi aniqlandi. Ishlab chiqilgan simulyatsion modellar yordamida ushbu parametrlar oralig'i o'rganilib, lazer kvantronining har bir konstruksiyasi uchun optimal parametrlar aniqlandi.




**10-rasm.** Trapezoidal lazer kvantroni uchun parametrlarni optimallashtirish asosida yutilish samaradorligini baholash.

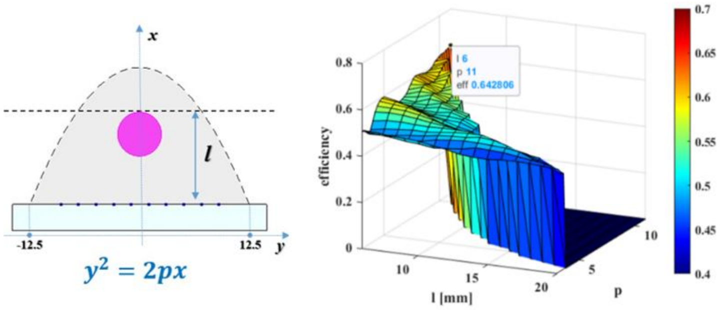
Trapezoidal kvantronning samaradorligini baholash uchun ikkita asosiy parametr sifatida l (6 mm dan 20 mm gacha, qadam: 1 mm) va h (10 mm dan 50 mm gacha, qadam: 1 mm) tanlandi. Bu yerda l — lazer kristalligacha bo'lgan masofa (uning diametri hisobga olingan holda), h esa 10-rasmda ko'rsatilganidek trapetsiyaning kichik asosidan kristallgacha bo'lgan masofa. h va l parametrlarining ikki o'lchamli funksiyasi sifatida keltirilgan yutilish samaradorligi qiymatlari shuni ko'rsatdiki, 0.57 teng maksimal samaradorlikka h = 10 mm va l = 6 mm bo'lganda erishish mumkin.




**11-rasm.** Geksagonal lazer kvantroni uchun parametrlarni optimallashtirish asosida yutilish samaradorligini baholash.

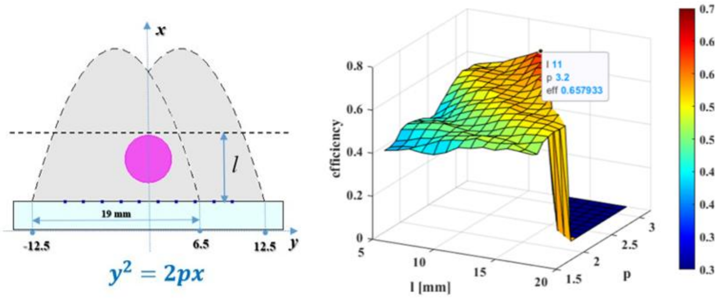
Geksagonal lazer kvantronining imkoniyatlari esa $\alpha$ ($0° \leq \alpha \leq 45°$, qadam: 1°) va h ($10$ mm $\leq h \leq 60$ mm, qadam: 1 mm) parametrlarini hisobga olgan holda baholandi. Bu yerda $\alpha$ 11-rasmda ko'rsatilganidek, yon devor tekisligi va yorug'lik diodi matritsasi o'rnatilgan devor orasidagi ikki yoqli burchak, h esa kristalldan yorug'lik diodi matritsasi joylashgan yuzaga parallel kichik asos devorigacha bo'lgan masofa. Ushbu konstruksiyaga ikki yoqli burchakni kiritishning asosiy maqsadi — yorug'lik diodining nurlanish yo'nalganlik qonuniyatlarini hisobga olish va lazer sterjeniga energiya uzatilishini samaradorligini oshirish edi. Simulyatsiya tadqiqotlari shuni ko'rsatdiki, $\eta_a = 0.54$ maksimal yutilish samaradorligiga $\alpha = 32°$ va h = 10 mm bo'lganda erishsa bo'ladi.

Tekis sirtli konstruksiyalariga alternativa sifatida optik damlash kamerasi uchun egrilangan sirtli – parabolik konfiguratsiyalar tadqiq qilindi. Parabolik silindr shaklidagi konstruksiyaning optimallashtiriladigan asosiy parametrlari sifatida parabola fokal parametri p (3 dan 11 gacha, qadam: 0.2), va l (6 mm dan 20 mm gacha, qadam: 1 mm) tanlandi, bu yerda l — lazer kristallgacha diametri inobatga olingan holda bo‘lgan masofa (12-rasm). Optimallashtirish natijalari shuni ko‘rsatdiki, ushbu konstruksiya uchun 0.64 maksimal yutilish samaradorligi l = 6 mm va p = 11 da erishiladi. Samaradorlik xaritasidan ko‘rinib turibdiki, samaradorlik 0.6 dan oshishi uchun l masofa 9 mm dan oshmasligi lozim. Bundan tashqari, simulyatsiyalar yana bir bor yorug‘lik diodi matritsasi va lazer kristalli orasidagi masofani minimal darajada bo‘lishi kerakligini tasdiqladi.



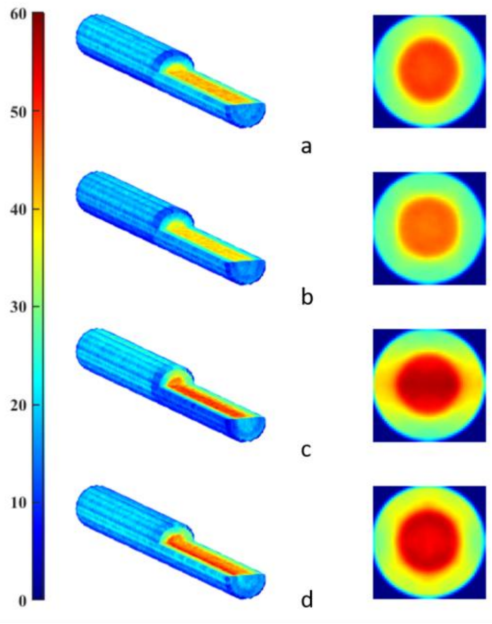

**12-rasm.** Parabolik silindr shaklidagi lazer kvantroni uchun parametrlarni optimallashtirish asosida yutilish samaradorligini baholash.

Keyingi konfiguratsiya — qo‘shaloq parabolik silindr shaklidagi lazer kvantonining konstruksiyasi ikkita bir xil parabolik silindrni (y o‘qi bo‘ylab -9.5 mm dan 9.5 mm gacha) o‘z ichiga oladi, ular x o‘qiga nisbatan simmetrik joylashgan bo‘lib bir xil masofaga shunday surilganki, y o‘qi bo‘ylab konstruksiya uzunligi 25 mm ni tashlik qiladi. Konfiguratsiyaning ko‘ndalang kesimi va simulyatsiya modeliga kiritilgan o‘lchamlarning tavsifi grafik tarzda 13-rasmda keltirilgan. E’tiborlisi, parabola shoxlari orasidagi optimal masofa 19 mm ham simulyatsiya natijalariga asoslangan holda tanlangan. Ushbu konfiguratsiyaning imkoniyatlari lazer sterjen va yorug‘lik diod matritsasi orasidagi masofani l (6 mm≤ l ≤ 18 mm, qadam: 1 mm) va parabolik parametrini (1.5 ≤ p ≤ 3.2, qadam: 0,1) o‘zgartirish orqali baholandi.Olingan samaradorlik taqsimotiga ko‘ra, ushbu konstruksiya uchun maksimal samaradorlik 0.66 ga teng bo‘lib, l = 11 mm va p = 3.2 da erishiladi. Umuman olganda, samaradorlikni 0.6 dan yuqori darajada ushlab turish uchun l ning optimal diapazoni [10, 14], p ning optimal diapazoni esa [2.6, 3.2]ni tashkil qildi.




**13-rasm.** Qo‘shaloq parabolik silindr shaklidagi lazer kvantroni uchun parametrlarni optimallashtirish asosida yutilish samaradorligini baholash.

Yuqori sifatli lazer chiqish nurlanishini olishda faol element ichidagi nurlanish (yutilish) taqsimoti ham muhim omil hisoblanadi. Har bir optimallashtirilgan lazer kvantronining yutilish taqsimoti ularning natijaviy ko‘ndalang kesim profillari bilan birga 14-rasmda keltirilgan.



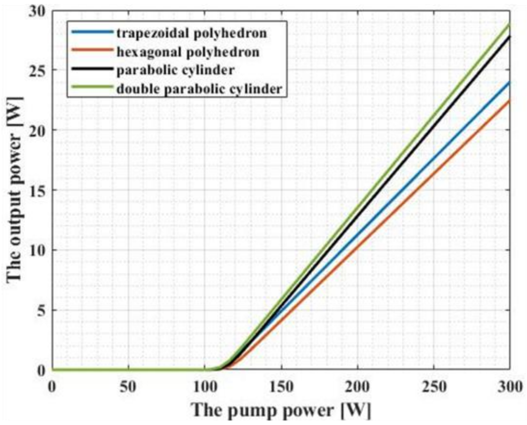
**14-rasm.** Optik damlash taqsimoti va mos ko‘ndalang kesim profillari: a) trapezoidal ko‘p qirralik; b) geksagonal ko‘p qirralik; c) parabolik silindr; d) qo‘shaloq parabolik silindr.

Olingan 3D yutilish taqsimotlari va ko‘ndalang kesim profillari ikki asosiy o‘ziga xos xususiyatni ko‘rsatdi: birinchidan, rangli ustunda aks ettirilgan ma’lumotlarga ko‘ra eng yuqori samaradorlik qo‘shaloq parabolik silindrda erishiladi (14d-rasm), eng past samaradorlik esa geksagonal ko‘p qirralikda kuzatiladi (14b-rasm); ikkinchidan, taqsimotlarning nisbiy bir jinsliligi va simmetriyasi ikki blokli konfiguratsiya va lazer kvantronlarining shakli bilan bog‘liq. Yutilgan nurlanishlarning asosiy qismi faol muhitning markaziy qismida to‘plangan, bu esa rezonator modasi va yutilish taqsimoti orasidagi yaxshi moslikni ta’minlaydi, natijada yuqori sifatli lazer dastasining hosil bo‘lishiga imkon beradi. Hozirgi vaqtga kelib, optik damlash kameralarning ichki devorlaridan maksimal qaytarish koeffitsiyenti 0.95 ga yetgan. Bu qiymatni simulyatsion modellarga kiritish orqali har bir lazer kvantron konfiguratsiyasi uchun yakuniy samaradorlik ko‘rsatkichlari olindi (1-jadval).

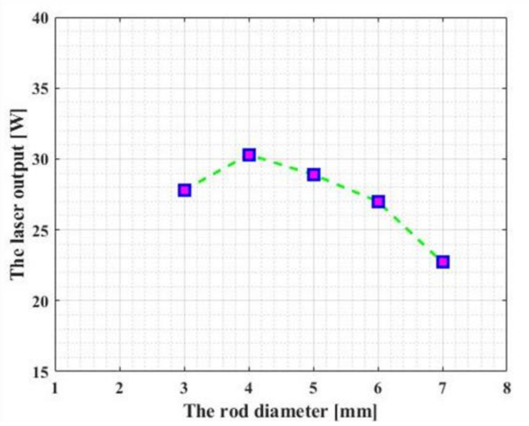
**Jadval 1. Optimizatsiya natijalari**

| **Lazer kvantron shakli** | **Optimal o‘lcham** | **Uzatish samaradorligi** | **Yutilish samaradorligi** |
|---|---|---|---|
| Trapezoidal ko‘p qirralik | l = 6 mm; h = 10 mm | $\eta_t$= 0.726±0.002 | $\eta_a$ = 0.641±0.002 |
| Geksagonal ko‘p qirralik | α = 32 °; h = 10 mm | $\eta_t$ = 0.703±0.002 | $\eta_a$ = 0.615±0.002 |
| Parabolik silindr | p = 11; l = 6 mm | $\eta_t$ = 0.783±0.002 | $\eta_a$ = 0.701±0.002 |
| Qo‘shaloq parabolik silindr | p = 3.2; l = 11 mm | $\eta_t$ = 0.788±0.002 | $\eta_a$ = 0.717±0.002 |

Bunda yorug‘lik diodi nurlanishining lazer sterjeniga uzatish samaradorligining eng yuqori 79% qiymati qo‘shaloq parabolik silindr kvantroni uchun olindi. Har bir yorug‘lik diodi ikkita blokdan iborat lazer tizimida 150 W quvvat (umumiy quvvat 300 W) taqdim eta olishi hisobi hamda rezonator va lazer sterjenining parametrlari (rezonator uzunligi: 12 sm, ichki yo‘qotishlar: 0,003 sm$^{-1}$, sterjen diametri: 5 mm sterjen uzunligi: 50 mm) ni inobatga olgan holda fazoviy bog‘liq tezlik tenglamalari asosida lazerning chiqish-kirish quvvat bog‘liqliklari olingan (15-rasm).Lazer sterjenining diametri lazerning ishlashiga qanday ta’sir qilishini o‘rganish maqsadida diametri 3 mm dan 7 mm gacha bo‘lgan sterjenlar ko‘rib chiqildi. Shu o‘rinda aytish joizki, har bir sterjen diametri uchun asosiy parametrlarning optimal qiymatlari alohida aniqlanishi kerak, ya’ni 4 mm diametrli sterjen uchun aniqlangan optimal lazer kvantron parametrlari 5 mm diametrli sterjen uchun mos kelmaydi. Shu sababli, biz faqat energiya uzatish samaradorligi eng yuqori bo‘lgan lazer kvantroni uchun, ya’ni qo‘shaloq parabolik silindr shaklidagi konfiguratsiya uchun lazer sterjenining optimal o‘lchamlari tadqiq qilindi. Dastlab, tanlangan konfiguratsiyaning har bir lazer sterjen diametri uchun optimal parametrlari aniqlandi va olingan ma’lumotlarga asoslanib natijaviy lazer chiqish quvvatlari solishtirildi (16-rasm). Simulyatsiyalar shuni ko‘rsatadiki, maksimal chiqish quvvati lazer sterjeni diametri 4 mm dan 5 mm gacha bo‘lgan oralig‘ida erishiladi. Ushbu diapazondan tashqarida lazerning chiqish quvvatlari pasayadi.




**15-rasm.** Optimallashtirilgan konfiguratsiyalar uchun kirish-chiqish quvvati munosabatlari.




**16-rasm.** Turli lazer sterjen diametrlari uchun lazer chiqish quvvatlari.

Simulyatsiya va hisoblash natijalari taklif etilgan konfiguratsiyalarni o‘z ichiga olgan yorug‘lik diodi lazer tizimlari boshqa optik damlanadigan lazerlar bilan qaysidir ma’noda raqobatbardosh samaradorlikka erishishi mumkinligini ko‘rsatdi. Chiqish-kirish quvvatlari bog‘liqliklari qo‘shaloq parabolik silindr konfiguratsiyasida lazer samaradorligining ko‘rib chiqilgan boshqa kvantronlarnikiga nisbatan yuqoriligini namoyish etdi va 30 W (optik samaradorlik 10%) chiqish quvvatiga erishish imkoniyatini ko‘rsatdi, bunda bo‘sag‘a optik damlash quvvati 120 W dan past bo‘lgan.

Samaradorlik nuqtai nazaridan yorug‘lik diodi lazerlar bugungi kunda lampa bilan optik damlanadigan lazerlar (juda keng polosali nurlanish spektriga ega) va diod bilan optik damlanadigan lazerlar (tor polosali nurlanish spektriga ega) o‘rtasida joylashgan. Ko‘rsatilgan 10% samaradorlik natijasi ma’lumot keltirilgan eksperimental ishda erishilgan natijalarni (optik samaradorlik ~ 6.3%) sezilarli darajada yaxshilaydi. Lampa bilan optik damlanadigan lazerlar (samaradorlik 5% gacha) bilan taqqoslaganda, bizning natijalarimiz ancha yuqori. Diod bilan optik damlanadigan lazerlar 80% gacha bo‘lgan optik samaradorlikka erisha olsa ham, yorug‘lik diodlari lazer diodlari bilan taqqoslaganda xarakteristikalar barqarorligi borasida ma’lum afzalliklarga ega.

# XULOSA

Mazkur dissertatsiya doirasida olib borilgan tadqiqotlar asosida quyidagi muhim natijalarga erishildi:

1. Yorug'lik diodlarining nurlanish jarayonlarini modellashtirishning yangi usuli taklif etildi, bu usul yorug'lik diodi qurilmalarining texnik tavsiflari asosida ularning chiqish (spektral va fazoviy) parametrlarini hisobga olish imkonini beradi;

2. Ilk bor yorug'lik diodlari bilan optik damlanadigan lazerlarning simulyatsiya modellari Monte-Karlo foton yo'lini kuzatish usuli asosida ishlab chiqildi va ular fazoga bog'liq tezlik tenglamalari bilan birgalikda yorug'lik diodlari bilan optik damlash, yorug'lik qaytishi, sinishi, yutilishi jarayonlarini, shuningdek, faol muhitdagi temperatura taqsimotini baholash imkonini beradi;

3. Yorug'lik diodi nurlanish energiyasini faol muhitga samarali o'tkazish mexanizmlari tahlil qilindi va turli lazer kvantron konfiguratsiyalari (tekis va egrilangan yuzali) baholandi. Taklif etilgan konfiguratsiyalar eksperimental natijalarga nisbatan differensial samaradorlikni 1.23 barobar va optik samaradorlikni 1.58 barobar oshirishi mumkinligi ko'rsatildi;

4. Yorug'lik diodi yordamida optik damlanadigan neodim qo'shilgan kristallarning imkoniyatlari, xususan, Nd:KGW ning imkoniyatlari simulyatsion tadqiqotlar orqali baholandi. Natijalar shuni ko'rsatadiki, Nd:KGW yutilish samaradorligida Nd:YAG dan ustun (mos ravishda 66.2% va 37.1%) va yuqori differensial samaradorlikni ko'rsatdi (mos ravishda 17.9% va 12.1%). Nd:KGW qisqaroq fluoressensiya yashash vaqti va past kvant chiqish samaradorligi sabab uning bo'sag'a optik damlash quvvati nisbatan yuqoriroq bo'ldi. Biroq, ushbu ko'rsatkich Nd:YAG nikiga yaqin bo'lib, yuqori quvvatli yorug'lik diodi yordamida optik damlanadigan Nd:KGW lazerlarga erishish mumkinligini ko'rsatadi;

5. Yorug'lik diodi nurlanishining temperaturaga bog'liq spektral siljishi faol muhitning yutilish xususiyatlariga ta'siri raqamli o'rganildi. Ko'k yorug'lik diodi nurlanishidagi 3-5 nm spektral siljish yutilish samaradorligini 5% dan ko'proqqa kamaytirishi mumkinligi aniqlandi;

6. Monte-Karlo fotonlarning yo'lini kuzatish modellashtirish usulidan foydalanib, ko'k yorug'lik diodlari yordamida ko'ndalang optik damlanadigan Ce:Nd:YAG lazerlari tadqiq qilindi. Tadqiqot natijalari Ce:Nd:YAG lazeri uchun 10% optik samaradorlik bilan 30 W dan ortiq lazer chiqish quvvatiga erishish imkoniyatini ko'rsatdi.

**SCIENTIFIC COUNCIL ON AWARDING OF SCIENTIFIC DEGREES PhD.03/30.09.2020.FM.55.04 OF URGENCH STATE UNIVERSITY NAMED AFTER ABU RAYHAN BIRUNI**

**INSTITUTE OF ION-PLASMA AND LASER TECHNOLOGIES**

**SHERMATOVA FERUZA ABDURASHID QIZI**

# LED-PUMPED NEODYMIUM LASERS

**01.04.11– Laser physics**

**ABSTRACT**
**of the dissertation for the doctor of philosophy (PhD) on physical and mathematical sciences**

**Urgench– 2025**

**The theme of doctor of philosophy (PhD) dissertation was registered at the Supreme Attestation Commission at the Ministry of Higher Education Science and Innovations of the Republic of Uzbekistan under number B2024.3.PhD/FM1163.**

The dissertation has been prepared at the Institute of Ion-plasma and laser technologies named after U.A.Arifov.

The abstract of the dissertation in three languages (Uzbek, English, Russian (resume)) has been posted on the website of the Scientific Council (www.urdu.uz) and on Information-educational portal «ZiyoNet» (www.ziyonet.uz).

| | |
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The defense will take place on « 15 » May 2025 at 14[00] at the meeting of the Scientific Council number PhD.03/30.09.2020.FM.55.04 at Urgench State University. (Address: 14 Kh. Olimjan str., Urgench city, 220100, Uzbekistan, Phone.: (99862)224-66-11, fax: (99862)224-67-00.)

The PhD dissertation is can be looked through in Information-resource centre at Urgench state university (is registered №797 (Address: 14 Kh. Olimjan str., Urgench city, 220100, Uzbekistan, Phone.: (99862) 224-66-11, fax: (99862)224-67-00.)

The abstract of the dissertation is sent out on « 7 » 05 2025.
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## INTRODUCTION (abstract of PhD thesis)

**Relevance and demand for the dissertation topic.** Nowadays, in the world, the development of affordable and efficient lasers remains one of the key tasks in the field of laser physics, which in turn requires continuous research on new optical pumping sources and corresponding active media. In recent years, significant achievements have been made in light-emitting diodes (LEDs) technology, especially in ensuring their output power and stability of characteristics, and in this regard, the development of new type LED-pumped lasers being at the center of global attention. LEDs have a number of advantages as optical sources, including high efficiency in converting electrical power to optical energy, low cost, compact structure, and long service life. Therefore, currently the study of efficient mechanisms for transferring energy from light-emitting diodes to a laser medium has become a particularly pressing issue, and it is considered important to conduct theoretical and applied research in this direction.

In recent years, a number of specialized scientific centers around the world – in the USA, France, China – have been conducting research on the properties of different laser active media that are suitable for optical pumping with light-emitting diodes, including new approaches for increasing the efficiency of LED-pumped lasers, such as using special optical materials—luminescent concentrators—for delivering energy from light-emitting diodes to the active medium, and developing new configurations of lasers operating on light-emitting diode radiation. In this field, key research directions include the effective delivery of light-emitting diode energy to the active medium, investigating active media with absorption properties matching the light-emitting diode emission spectrum, studying energy transfer mechanisms between active ions in the laser medium, including transitions in laser energy levels, and analyzing these mechanisms. Additionally, in-depth studies of the physical processes related to the conversion of light-emitting diode radiation into laser radiation, developing simulation models of light-emitting diode-pumped lasers to identify effective laser configurations, optimizing them, and applying them in practice are considered urgent tasks.

Recently, in the Republic of Uzbekistan, systematic measures are being implemented to scientific tasks related with the study new possibilities for the efficient use of energy, particularly development of innovative energy-saving technologies, investigation of new approaches for energy conversion along with to support and encourage innovation activities grounded on scientific achievements at the state level. In the Strategy for Innovative Development of the Republic of Uzbekistan for 2022–2026, tasks such as "...stimulating demand for innovation by ensuring a comprehensive system from the idea to the end consumer for the creation of new types of products and innovative technologies"[4] have been defined. In the implementation of these tasks, among the important issues are the investigate of physical processes related to the development of new types of energy- and cost-efficient light-emitting diode-pumped lasers, the exploration of active media and

[4] Decree of the President of the Republic of Uzbekistan, No.DP-165 dated 06.07.2022.

corresponding sensitizers to enhance efficiency of direct conversion of light-emitting diode energy into laser energy, and the creation of of laser simulation models to develop prototypes of light-emitting diode-pumped lasers further.

This dissertation research to a certain extent corresponds to the tasks outlined in the Decree of the President of the Republic of Uzbekistan No. PF-6097 dated October 29, 2020, “On the approval of the Concept of Science Development until 2030,”[5] the Decree of the President of the Republic of Uzbekistan No. PF-60 dated January 28, 2022, “On the Development Strategy of the New Uzbekistan for 2022 — 2026,”[6] as well as other normative-legal documents relevant to this scientific activity.

**Alignment of the research with priority areas of science and technology development in the republic**. This research work is in line with the priority areas of science and technology development in the Republic of Uzbekistan: PFI-2 “Energy, Energy Saving, and Alternative Energy Sources: - Study of scientific problems of improving energy grid efficiency based on innovative energy-saving technologies.”

**Degree of study on the problem**. A number of important scientific studies in this area have been conducted in various international research centers, including evaluations of the efficiency of different LED-pumped laser configurations to improve their output parameters. Significant results in this field have been achieved by foreign scientists, such as those from the USA (B. Villars, E.S. Hill, C.G. Durfee), France (A. Barbet, F. Balembois, F. Druon, P. Pichon, A. Paul, P. Georges, and others), Korea (K.Lee, H.C.Lee, J.Y.Cho, J.C.Lee, J.Yi), China (J. Shen, S. Jiang, X. Huang, R. Jiang, P. Lu, S. Xu, and others), Iran (S.M. Zahedi, A.H. Farahbod, M. Mahmoudi), and others.

American scientists achieved a maximum of 18 mJ of laser energy using Ce:Nd:YAG active medium with transverse pumping scheme.

French scientists proposed a new LED pumping concept involving the use of luminescent concentrators as frequency converters (wavelength) of the radiation. The main goal of this pumping scheme is to maximize LED light collection and enhance photon absorption by overlapping a larger emission spectral range. Using this method, laser crystals such as Ti:Sa, Nd:$YVO_4$, Cr:LiSAF, and others were studied.

J.Shen and colleagues experimentally achieved high optical conversion efficiencies of LED energy into laser radiation energy with an Nd:YAG and Nd:glass active medium, reaching 8% and 10.9%, respectively.

However, the potential neodymium ions doped crystal structures with host matrices other than yttrium-based ones, as well as neodymium crystals doped with sensitizer ions in LED pumping, remains unexplored. Despite recent advancements in LED-pumped lasers, there have been no reports of these systems achieving competitive power levels or sufficient conversion efficiency. It can be explained, first of all, by incomplete study of effective mechanisms for transferring LED energy

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[5] Decree of the President of the Republic of Uzbekistan, No. DP-6097 dated 29.10.2020.
[6] Decree of the President of the Republic of Uzbekistan, No. DP-60 dated 28.01.2022.

to the active medium, as well as insufficient consideration of the specific characteristics of LED radiation in the development of laser systems.

**Connection of the dissertation tasks with the research plans of the institution.** The dissertation work was conducted within the framework of the state-funded theme of the Institute of Ion-Plasma and Laser Technologies of the Academy of Sciences of the Republic of Uzbekistan: “Investigation of mechanisms for improving the efficiency of lasers excited by various methods based on the use of new materials and technologies” (2021–2024).

**The purpose of the research work** is to identify the primary factors limiting the efficiency of converting LED energy into laser radiation under direct pumping conditions and to propose solutions for developing highly efficient laser devices based on neodymium laser crystals.

**Research tasks:**

- to develop simulation models for LEDs;

- to develop simulation models of LED-pumped lasers to analyze their output characteristics;

- to investigate mechanisms for efficient energy transfer of LED emission to the active medium.

- to explore neodymium-doped crystals with alternative matrices to enhance absorption efficiency in LED-pumped lasers;

- to study the influence of spectral shifts in the LED emission spectrum on the laser performance;

- to study the potential of neodymium crystal doped with sensitizing ions of $Ce^{3+}$ in LED-pumping laser systems.

**Study object:** LEDs, solid-state neodymium laser active media, sensitizers, and various laser cavity configurations.

**Study subject:** Physical processes of photon interaction with the laser active medium, sensitizer, photon absorption, luminescence, energy transfer from sensitizer ions to active ions, and the process of laser emission in various active media under LED pumping.

**Research methods.** The dissertation uses methods based on the simulation of physical processes in laser systems, considering the spectral characteristics of active media and LED emission. The simulation models were developed based on Monte Carlo photon tracing technique.

**The scientific novelty of the research** is as follows**:**

a novel approach for modeling LED emission processes was proposed, which allows taking into account the spatial and spectral output parameters of LED devices directly from their technical datasheet;

for the first time, simulation models of LED-pumped lasers were developed based on Monte Carlo photon tracing technique;

modeling results determined that curved laser cavities outperform planar ones by 5–6% in absorption and energy transfer efficiency in LED-pumped laser systems;

it was revealed that Nd:KGW laser rod has high potential compared to Nd:YAG in LED-pumped laser systems;

it was found that the temperature-dependent spectral shift in LED emission significantly influences the absorption properties of the laser active medium, specifically a spectral shift of 3–5 nm can lead to a reduction in absorption efficiency exceeding 5%;

simulation results revealed that optical-to-optical efficiencies of up to 10% and output powers exceeding 30 W are attainable in Ce:Nd:YAG laser systems in a transverse pumping scheme with blue LEDs.

**The practical results of the research** are as follows:

a new approach has been developed for modeling the radiation processes of light-emitting diodes;

simulation models of LED-pumped lasers have been developed based on the Monte Carlo photon path tracing method;

it has been substantiated that a laser output power of 31 W and an optical efficiency of 10.3% can be achieved in transversely LED-pumped Nd:KGW laser systems;

it has been substantiated that in transversely LED-pumped Ce:Nd:YAG laser systems, it is possible to achieve a laser output power exceeding 30 W with an optical efficiency of 10%.

**The reliability of the research results** is supported by the use of modern methods and approaches in photonics. The conclusions are grounded in fundamental theoretical studies on the physical mechanisms processes in laser media and are fully consistent with findings from other researchers.

**Scientific and practical significance of the results.**

The scientific significance of the research results is explained by the fact that the proposed active media (Nd:KGW, Ce:Nd:YAG) and laser cavity configurations for LED-pumped lasers can significantly increase the efficiency of such lasers, and that the developed models of LED-pumped lasers can be used for theoretical studies.

The practical significance of the research results is explained by the fact that the proposed scientific and technical solutions can be applied in the development of new efficient technologies related to the conversion of LED energy into laser energy.

**Implementation of research results.** The results of the research conducted on the absorption, thermal properties, and laser emission characteristics of active media such as Nd:YAG, Ce:Nd:YAG, and Nd:KGW under LED pumping have been applied in the following scientific research projects:

the findings were used in fundamental research of the state-funded theme “Modeling the processes of scattering, adsorption, and encapsulation of atoms by carbon nanostructures and the theoretical investigation of elastic electron scattering from spherical fullerenes,” carried out at the U.A. Arifov Institute of Ion-plasma and laser technologies (Certificate 2/1255-2798 from the Academy of Sciences of the Republic of Uzbekistan, dated December 17, 2024), for the development of a computer model of carbon nanotubes. The obtained results made it possible to evaluate the influence of temperature on the scattering of atoms in carbon nanotubes.

algorithms developed for the first time based on the Monte Carlo method for optimizing the domain sequence for generating third harmonics in crystals with non-uniform domain structures were employed in the Uzb-Ind-2021-96 project

“Development of methods for obtaining sources of multicolor ultrashort laser pulses as a result of parametric effects of femtosecond laser pulses in nonlinear photonic crystals”, conducted at Tashkent state technical university (Certificate 01/9-14-1717 of Tashkent state technical university dated October 11, 2024). The application of the results provided significant data on the parametric amplification of short laser pulses in nonlinear photonic crystals, which, in turn, facilitated the development of innovative optimization methods.

**Testing of research results.** The dissertation’s findings were reported and discussed at 8 international and republican conferences.

**Publication of research results.** The results were published in 14 scientific papers, including 5 articles in journals recommended by the Supreme Attestation Commission of the Republic of Uzbekistan for publication of main dissertation results, and 1 software product registration certificate was obtained.

**Structure and volume of the dissertation.** The dissertation consists of an introduction, four chapters, a conclusion and a list of references including 43 figures and 6 tables. The text of the dissertation is presented on 104 pages.

## MAIN CONTENT OF THE DISSERTATION

**The introduction** of the dissertation substantiated the relevance and demand of the research, formulated the research purpose and tasks, defined the object, subject, and methods of research, and outlined the connection of the dissertation research with the priority areas of science and technology development in the country. The scientific novelty of the research was described, the reliability of the obtained results was justified, their theoretical and practical significance was revealed, and the implementation and testing of the results, as well as the volume and structure of the dissertation, were presented.

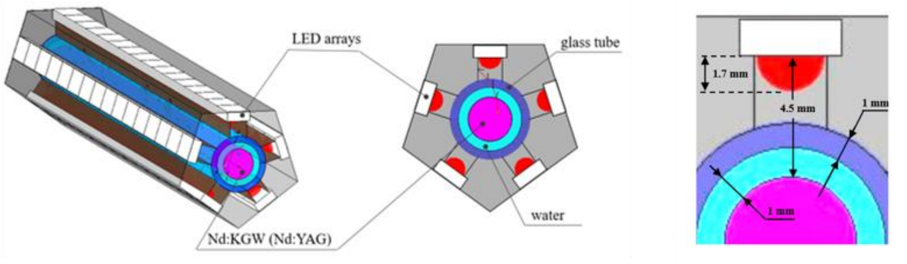
**The first chapter** of the dissertation, titled **“Current state of LED-pumped lasers,”** presents an analysis of the literature on the current state of LED pumping, along with a brief review of the key parameters and characteristics of LEDs that directly influence the optical pumping process. The literature analysis indicates that over the past four decades, the power of continuous-mode LED illumination has significantly improved, increasing by two to three orders of magnitude. Despite this, LED-based pumping power still lags behind laser diodes, which typically achieve illumination levels in the range of tens of $kW/cm^2$.

LED pumping remains a relatively specialized field due to the small number of laboratories focused on LED-based pumping. This limited coverage highlights both an opportunity for research and the necessity for further studies in this area. Since LEDs are Lambertian light sources, transverse pumping schemes are preferable for more efficient energy transfer into the solid-state active medium. LEDs operate in pulsed (quasi-continuous) mode to achieve high output power levels during pumping. This mode significantly increases radiation power over short intervals while helping to reduce heating issues within the laser rod. However, it may also lead to a spectral shift in LED emission, which in turn can influence the absorption properties of the active medium.

Taking all the above into account, it can be concluded that the development of LED-pumped lasers is still in its early stages, with several challenges requiring innovative solutions. Based on the analysis of the current state of LED-pumped lasers, the main tasks of the dissertation have been formulated.

**The second chapter**, titled **"Modeling of physical processes in LED-pumped lasers,"** is devoted to the development of models for LED-pumped lasers on the MATLAB® programming and numerical computation platform using Monte Carlo photon tracing. A new method is proposed for accounting for the spectral and spatial characteristics of LED emission directly from their technical specifications. This method simplifies the modeling process by eliminating the need to simulate optical processes in secondary optics within the devices while maintaining high accuracy. The interaction of LED photons with matter is also considered within the chosen modeling method, including pumping processes, absorption, reflection, refraction, and other optical processes. The advantages and disadvantages of the selected modeling approach for LED pumping are discussed: Monte Carlo photon tracing is well-suited for modeling physical processes related to radiation from complex light sources such as LEDs. This chapter also presents spatially dependent rate equations used in calculating the output power of LED-pumped lasers. The choice of these equations is justified by the non-uniform absorption distribution of LED radiation within laser crystals.

**The third chapter**, **"LED-pumped Nd:YAG and Nd:KGW lasers,"** presents research results obtained using simulation methods for an Nd:KGW LED-pumped laser. The majority of experimental studies on obtaining laser radiation using LED pumping conducted to date have been performed on Nd:YAG crystals. The potential of neodymium ions in combination with other host matrices under LED pumping conditions remains insufficiently explored. One of the alternative host matrices for neodymium is KGW (potassium gadolinium tungstate), and the active medium based on this crystal structure exhibits a larger emission cross-section compared to well-studied LED-pumped laser crystals such as Nd:YAG and Nd:$YVO_4$, while also featuring a broad absorption range at a wavelength of 808 nm.




a b c

**Figure 1.** General (a) and cross-sectional (b) views of the modeled laser cavity with technical specifications.

To completely evaluate the potential of Nd:KGW for LED pumping, a comparative study of Nd:KGW and Nd:YAG LED-pumped lasers was conducted. In this study, to ensure identical pumping conditions for the Nd:KGW and Nd:YAG lasers, simulation models were developed based on a cavity "five-pass pumping module,” similar to the one used in a recent experimental study of LED-pumped Nd:YAG laser (Fig. 1).

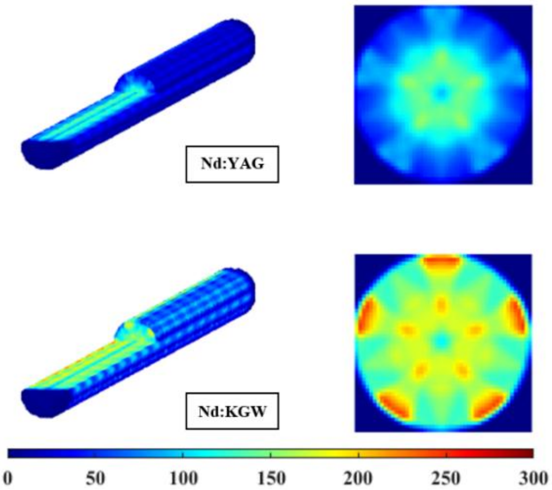



**Figure 2.** Absorption distributions.

Based on the data obtained from the simulation model, it was found that the absorption efficiency of Nd:KGW significantly exceeded that of Nd:YAG. The absorption distributions and the color bar shown in Fig. 2 provide a visual representation of the pumping efficiency, as well as the uniformity and non-uniformity of the absorbed power distribution. These distributions were calculated using a statistical sample of 10 million photons emitted by each LED, and the values on the color bar correspond to the number of absorbed photons in each volumetric cell (the laser crystal is divided into 50×50×200 cells along the x, y, and z axes).

In general, this result was expected due to the higher concentration of active neodymium ions and the greater spectral overlap between LED emission and the absorption spectrum of Nd:KGW. The absorption efficiency estimated through modeling demonstrates the superiority of Nd:KGW (66.2%) over Nd:YAG (37.1%) in terms of the percentage of absorbed photons (with neodymium ion concentrations of 3% and 1% in the respective host-matrices). Subsequently, a comparative analysis of the output parameters of 3% Nd:KGW and 1% Nd:YAG was conducted (Fig. 3).

Due to its superior absorption efficiency, Nd:KGW outperforms Nd:YAG, demonstrating higher slope efficiency (17.9% and 12.1%, respectively). As anticipated from the properties of Nd:KGW—specifically, its shorter fluorescence lifetime and lower quantum yield—it exhibits a higher threshold power. However, this value remains relatively close to that of Nd:YAG, indicating the attainment of a high-power LED-pumped laser using Nd:KGW appears feasible.

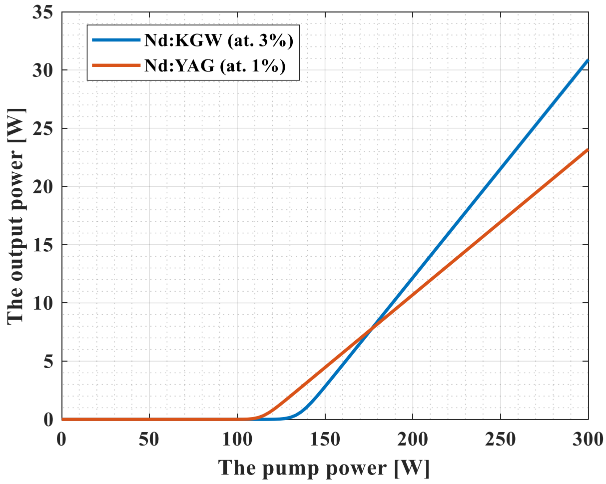



**Figure 3.** Input – output power relationship (Nd:KGW vs Nd:YAG).

It should be noted that the input-output power dependencies presented in Fig. 3 were obtained under the assumption of optimal cooling conditions for the laser systems. In reality, as noted in the literature, the lower thermal conductivity and anisotropy of the KGW matrix pose a critical challenge in laser devices, where efficient heat dissipation is necessary to maintain stable operation and high performance. In LED-pumped laser systems, heat accumulation in the laser medium can lead to thermal lensing, where temperature gradients cause changes in the refractive index of the crystal. This phenomenon can affect the output laser beam and reduce the overall efficiency of the system. Early studies of Nd:KGW lasers with other optical pumping sources highlight thermal effects as a major limitation in utilizing this crystal. This raises an important question: to what extent will accounting for thermal load impact the obtained output power results in LED-pumped systems? To investigate this, as an initial step, temperature distributions within the active media were calculated based on heat equations (Fig. 4) at various pump power levels, taking into account the respective physical properties of Nd:YAG and Nd:KGW laser rods.

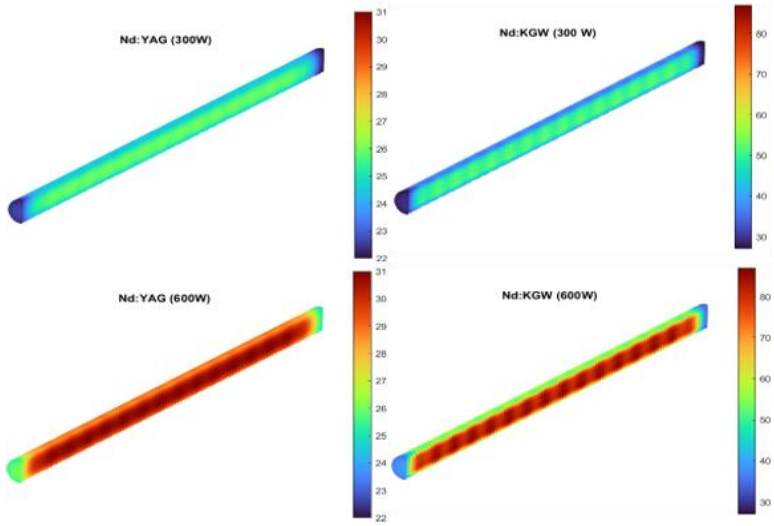


**Figure 4.** Temperature distributions.

Nd:YAG exhibits minimal heating at both 300 and 600 W, maintaining a temperature difference between the crystal's center and edge below 5 degrees. In contrast, Nd:KGW displays a notable divergence, showing a temperature rise of 90 degrees at the higher power of 600 W, accompanied by a temperature gradient (difference between center and edge) of approximately 30 degrees. Employing a faster coolant flow rate could potentially alleviate this gradient, especially considering the transverse pumping scheme used. Additionally, most LED-pumped lasers today utilize pulsed pumping (quasi-continuous pumping mode) to increase the optical power of the LEDs, which helps mitigate thermal issues in the active medium. Therefore, regarding the earlier question posed, thermal factors should not significantly influence the results presented in Fig. 3, which demonstrate the superior performance of Nd:KGW compared to Nd:YAG in LED-pumped laser systems.

**The fourth chapter**, titled **"Simulation model of LED-pumped Ce:Nd:YAG laser,"** examines the mechanisms of efficient energy transfer from LED emission to the active medium by optimizing the parameters of proposed planar and curved laser cavities. The potential of neodymium-doped crystals with sensitized ions in LED-pumped systems based on Ce:Nd:YAG was also explored. Additionally, this chapter investigates, through simulation studies, the impact of temperature-dependent spectral shifts in LED emission on the absorption properties of the active medium.

The potential of Ce:Nd:YAG laser crystals for LED pumping has been previously considered in several experimental studies. Using one of these studies as a starting point, an initial simulation model of the Ce:Nd:YAG laser system was developed (Fig. 5). In this experimental study, the output parameters of the laser

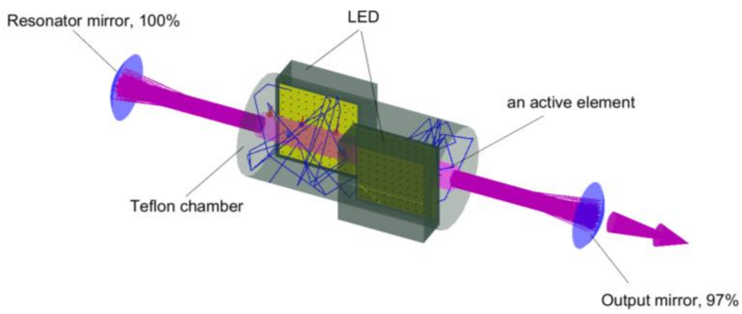



**Figure 5.** General view of the simulated laser system.

were compared under a transverse pumping scheme for Ce:Nd:YAG laser rods of different diameters (3 mm and 6 mm): the highest slope efficiency of 12.8% was achieved with a 6 mm diameter Ce:Nd:YAG laser rod.

Despite the significant progress in LED technologies, the low power output characteristics of LEDs continue to pose obstacles in the development of LED-pumped lasers. Technically, the threshold pump power can be achieved by switching on the LED at certain intervals, specifically using the so-called QCW mode. Compared to the continuous-wave (CW) mode, the QCW mode presents additional challenges due to higher currents, voltages, and consequently, elevated temperatures within the LED. These thermal effects can cause a spectral shift in the emission of the pump source. Spectral shift can lead to changes in the overlapping between the LED emission spectrum and the lasing medium absorption spectrum. Therefore, one of the key objectives of this dissertation was to investigate the impact of LED emission spectral shift on the pumping characteristics of an LED-pumped laser. To study this effect, experimental data on the emission spectra of blue LEDs measured at different temperatures were used. These emission spectra were numerically processed (Fig. 6) and incorporated into a validated simulation model of the LED-pumped laser (Fig. 5). The pumping characteristics are primarily determined by two key parameters: pump efficiency and absorption distribution, both of which significantly influence laser performance. Initially, using the simulation model, the pump efficiencies were determined for each spectrally shifted input corresponding to LED emissions under the same photon statistics and identical pumping conditions.

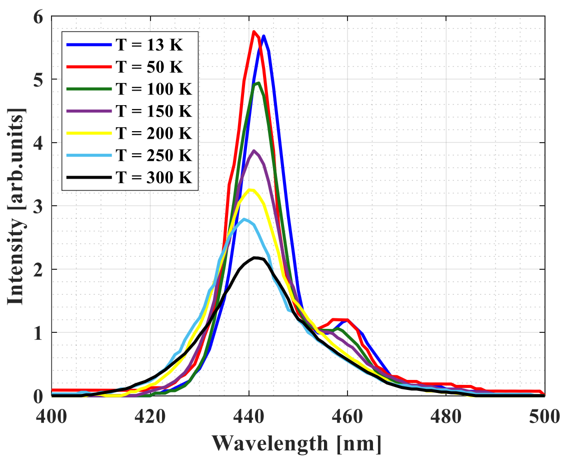



**Figure 6.** Numerically processed experimental emission spectra of a blue LED at different temperatures.

The maximum discrepancy in terms of pump efficiency (absorption) due to varying temperatures amounted to 5.4%, the difference between spectra at T=13 K and T=250 K. For the rest of the temperature range of 13–300 K, the photon absorption efficiencies, calculated from our modeling results, were found to be within the range of 0.388–0.41 (Fig. 7). Next, absorption distributions were obtained for each temperature based on experimentally measured optical emission spectra of the LED. Figure 8 illustrates the shape and scale of variation in the pump distributions for four selected temperatures It can be inferred that at low temperatures, more distinct absorption regions are observed in the active medium. While the general form of the absorption distribution within the laser crystal remains consistent, there is a noticeable pattern of decreased absorption properties as the operating temperature of the LED increases.

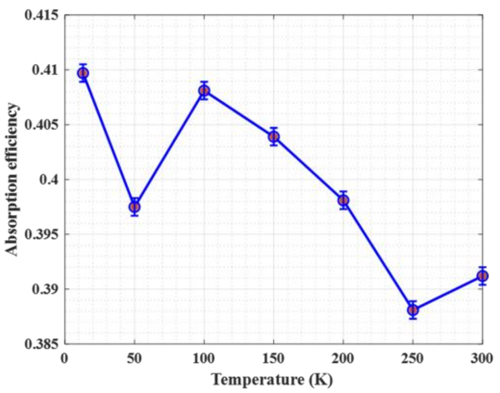



**Figure 7.** Absorption efficiencies depending on temperatures within LED.

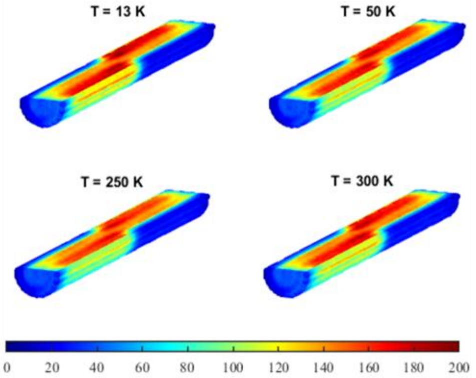



**Figure 8.** Absorption distributions of photons within active medium for operating temperature range 13-300 K of LED.

Following the validation of the simulation model, we optimized the laser system based on the Ce:Nd:YAG active medium by modifying the laser cavity designs. We developed simulation models for four types of laser cavities: trapezoidal polyhedron, hexagonal polyhedron, parabolic cylinder, and double parabolic cylinder (Fig. 9).

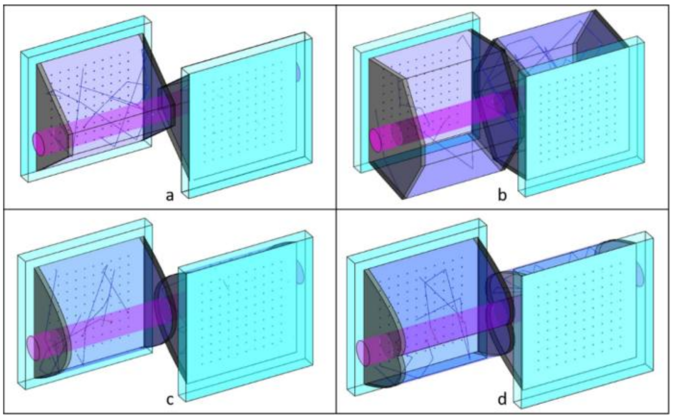



**Figure 9.** General view of the proposed laser cavities in the shape of: a) a trapezoidal polyhedron; b) a hexagonal polyhedron: c) a parabolic cylinder; d) a double parabolic cylinder.

Aiming to achieve a relatively uniform absorption distribution, the referenced work uses a two-LED system with LEDs positioned on opposite sides of the laser rod and shifted along the optical axis of the rod. Following this approach, we considered the cavities as consisting of two identical cavity blocks and a single laser rod: both blocks share a rod diameter of 5 mm, with one block having a length of 25 mm. The combined length of the two-block system remains 50 mm. To simplify cavity analysis, we initially focused on studying a single block in terms of absorption efficiency. For this purpose, two key parameters were selected for each configuration, and a range of their physically realizable space was determined. Using the developed simulation models, this parameter space was explored to identify the optimal parameters for each laser cavity design.

To evaluate the performance characteristics of the trapezoidal cavity, we selected two key parameters: l (ranging from 6 mm to 20 mm in 1 mm increments) and h (ranging from 10 mm to 50 mm in 1 mm increments). Here, l - represents the distance from the LED array to the laser crystal, accounting for its diameter, while h corresponds to the distance from the crystal to the small base of the trapezoid, as illustrated in Figure 10. The absorption efficiency values, represented as a two-dimensional function of h and l indicate that maximum absorption efficiency of 0.57 will be attained when h = 10 mm and l = 6 mm.

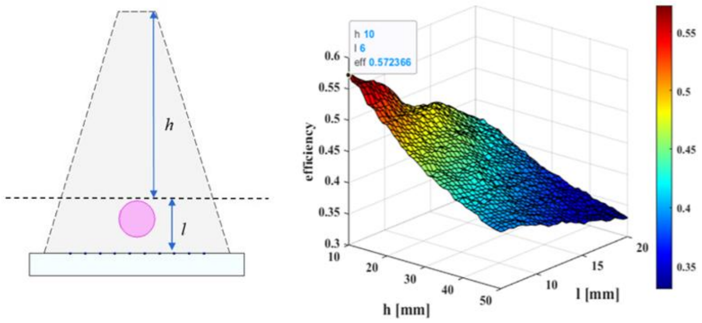


**Figure 10.** Estimation of the absorption efficiency for a trapezoidal laser cavity based on parameter optimization.

The capabilities of the hexagonal laser resonator were estimated for parameters α (0° ≤ α ≤ 45°, step: 1°) и h (10 mm ≤ h ≤ 60 mm, step: 1 mm), where α is the dihedral angle between the plane of the side wall and the wall containing the LED array, h is the distance from the crystal to the small base, parallel to the surface with the LED array, as shown in Figure 11. The primary motivation for incorporating a dihedral angle into the design was to address the divergence of the LED radiation pattern and achieve more efficient coupling of light into the rod. Simulation studies have shown that maximum absorption efficiency $\eta_a$ = 0.54 can be achieved at α = 32° and h = 10 mm.

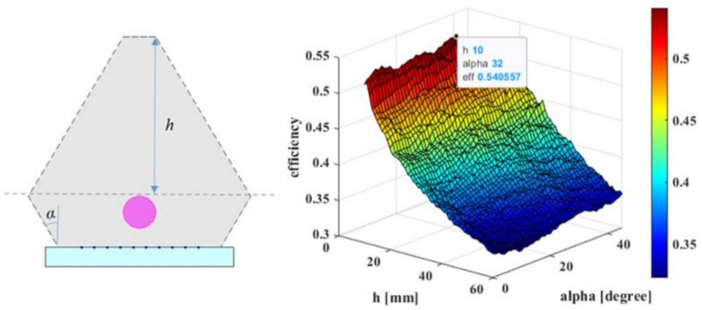


**Figure 11.** Estimation of absorption efficiency for a hexagonal laser cavity based on parameter optimization.

As an alternative to the polyhedral designs, we also explored curved pumping chambers — parabolic configurations. The key parameters for the parabolic cylinder configuration were the focal parameter p (ranging from 3 to 11 with a step of 0.2) and l (ranging from 6 mm to 20 mm with a step of 1 mm), where l is the distance from the LED array to the laser crystal, accounting for its diameter (Figure 12). The optimization results show that the maximum pumping efficiency of 0.64 for this design is achieved at l = 6 mm and p = 11. The efficiency

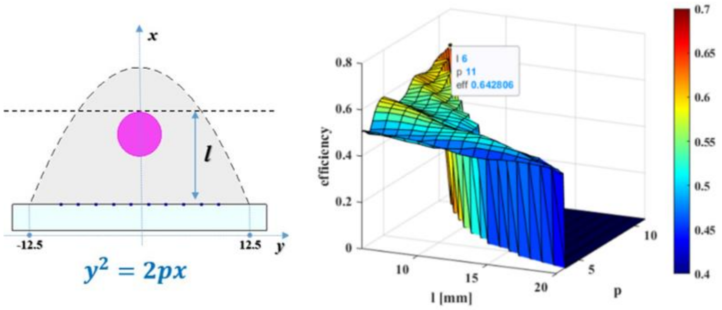


**Figure 12.** Estimation of absorption efficiency for laser cavity in the shape of a parabolic cylinder based on parameter optimization.

map indicates that to achieve absorption efficiency of more than 0.6, l must not exceed 9 mm. Further, the simulations one more time confirm that the distance between the LED array and the laser rod should be minimized.

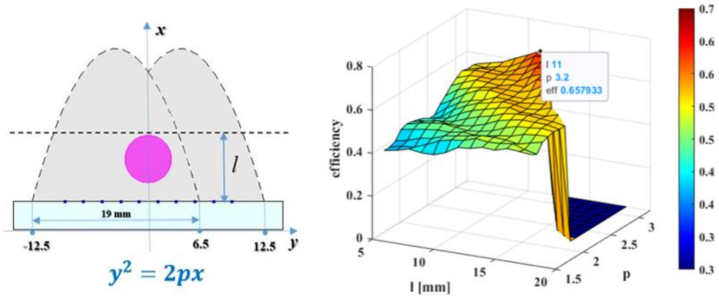



**Figure 13.** Estimation of absorption efficiency for laser cavity in the shape of a double parabolic cylinder based on parameter optimization.

The next configuration – a double parabolic cylinder laser cavity. It consists of two identical parabolic cylinders (along the y -axis from -9.5 mm to 9.5 mm), symmetrically placed relative to the x -axis and shifted by the same distance such that the length of the configuration along the y -axis is 25 mm. The cross-section and corresponding explanation of the entered parameters are graphically depicted in Figure 13. It is noteworthy that the optimal value of the distance (19 mm) between the branches of the parabola was chosen based on the modeling results. The capabilities of this design were evaluated by introducing the distance between the rod and the LED matrix l (6 mm ≤ l ≤ 18 mm, step: 1 mm) and the parabolic parameter (1.5 ≤ p ≤ 3.2, step: 0.1). In general, to achieve an absorption efficiency exceeding 0.6, the optimal interval for l ∊ [10, 14] and for p ∊ [2.6, 3.2].

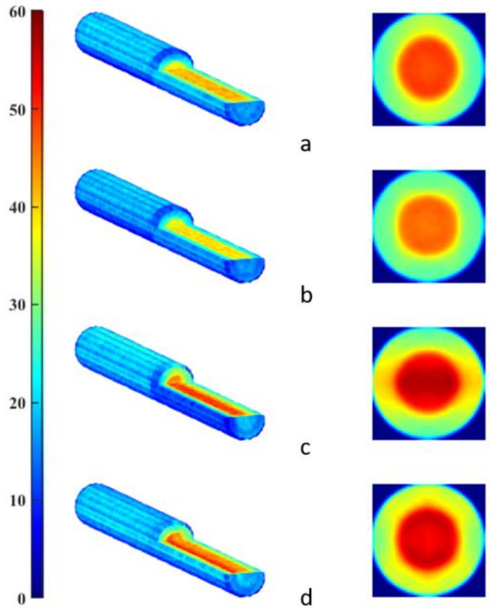



**Figure 14.** Distributions and corresponding cross - section profiles for a) a trapezoidal polyhedron; b) a hexagonal polyhedron; c) a parabolic cylinder; d) a double parabolic cylinder.

The absorption distribution within the crystal is also a significant factor in obtaining a high-quality laser beam at the output. Absorption distributions for each optimal cavity shapes, identified in previous sections, are shown in Figure 14, along with their resulting cross-sectional profiles.

The 3D distributions and cross-section plots reveal two key features: firstly, the color bar indicates absorption efficiencies, with the highest efficiency achieved in a double parabolic cylinder (Figure 14d) and the lowest efficiency in a hexagonal polyhedron (Figure 14b); secondly, the relative uniformity and symmetry of the cross-sections are due to the symmetrical two-block pumping systems and cavity shapes. The highest absorbed radiation is concentrated in the central part of the active medium, facilitating good overlap between the resonator mode and the absorption distribution, thereby contributing to the generation of high-quality laser beams. The highest reflectivity coefficient from the inner walls of the pumping chambers achieved to date is 0.95. By incorporating this value into the simulation models, final efficiency parameters for each laser cavity configuration were obtained (Table 1).

**Table 1. Optimized results**

| Cavity shape | Optimal size | Transfer eff. | Absorption eff. |
|---|---|---|---|
| Trapezoidal polyhedron | l = 6 mm; h = 10 mm | $\eta_t$= 0.726±0.002 | $\eta_a$ = 0.641±0.002 |
| Hexagonal polyhedron | α = 32 °; h = 10 mm | $\eta_t$ = 0.703±0.002 | $\eta_a$ = 0.615±0.002 |
| Parabolic cylinder | p = 11; l = 6 mm | $\eta_t$ = 0.783±0.002 | $\eta_a$ = 0.701±0.002 |
| Double parabolic cylinder | p = 3.2; l = 11mm | $\eta_t$ = 0.788±0.002 | $\eta_a$ = 0.717±0.002 |

In this case, the highest transfer efficiency of emission from the LED to the laser rod, 79%, was achieved for the laser cavity in the shape of a double parabolic cylinder. Considering each LED provides 150 W in the two-block laser system (total power – 300 W), and the parameters of the resonator and laser rod (resonator length: 12 cm, internal losses: 0.003 $cm^{-1}$, rod diameter: 5 mm, rod length: 50 mm), input – output power relationships were obtained using space-dependent rate equations (Fig. 15). To investigate the influence of rod diameter on laser performance, we evaluated rods with diameters ranging from 3 mm to 7 mm. It is important to note that for each rod diameter, the optimal values of key parameters should be determined separately, the optimal parameters for a laser cavity with a 4 mm diameter rod will not be suitable for a 5 mm diameter rod. Therefore, the optimal laser rod dimensions were investigated only for the laser cavity with the highest energy transfer efficiency, specifically for the double parabolic cylinder configuration. First, the optimal parameters for each rod diameter in the chosen configuration were determined, and then, based on the obtained data, the laser output power results were compared (Fig. 16). Simulations reveal an optimal diameter range of 4 mm to 5 mm, where lasers achieved superior performance. Outside this range, laser outputs decrease.

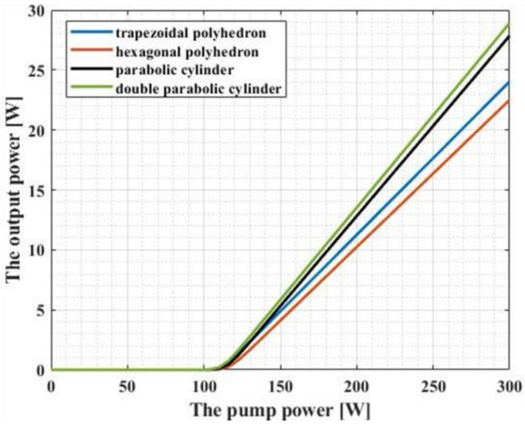



**Figure 15.** Input – output power relationship for optimized configurations.

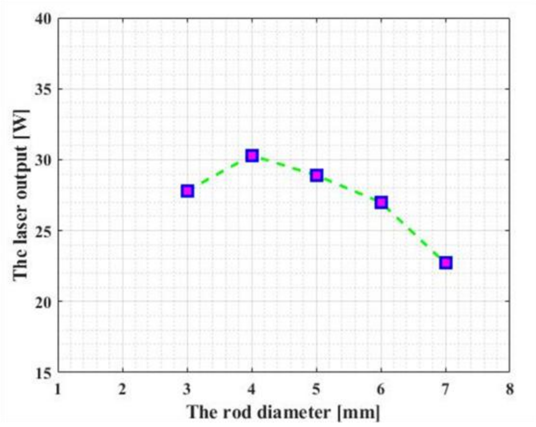



**Figure 16.** Laser output powers for different rod diameters.

The simulation results and numerical calculations suggest that lasers incorporating the proposed configurations are expected to achieve competitive efficiency compared to lasers with other types of optical pumping. The input- output relationship indicate the superior performance of the laser with the double parabolic cylinder configuration compared to other considered laser cavities and suggest the possibility of achieving an output power of 30 W (conversion efficiency of 10%) at a threshold pump power of less than 120 W.

In terms of efficiency, LED lasers fall between lamp-pumped lasers (which have a very broadband pump spectrum) and diode-pumped lasers (which have a narrowband pump spectrum). Our demonstrated efficiency of 10% significantly improves upon the referenced experimental work (optical-to-optical efficiency ~ 6.3%). Compared to lamp-pumped lasers (efficiency up to 5%), our results are significantly higher. While diode-pumped lasers can achieve optical-to-optical efficiencies as high as 80%, LEDs offer certain advantages over diodes in terms of characteristic stability.

## CONCLUSIONS

Based on our study in this PhD thesis, we reached following conclusions:

1. A novel approach to modeling the emission process of light-emitting diodes is proposed, which allows taking into account the output parameters (spectral and spatial) of LED devices directly from their datasheet specifications;

2. For the first time, simulation models of LED-pumped lasers were developed based on Monte Carlo photon tracing technique, which along with space-dependent rate equations allow to evaluate processes of pumping, reflection, refraction, absorption of LED radiation, as well as thermal distribution within the active medium;

3. Efficient energy transfer mechanisms of LED emission to the active medium were analyzed, and various laser cavity configurations (with planar and curved surface) were evaluated. The proposed configurations contributed to improvement in slope efficiency by 1.23 times and optical-to-optical efficiency by 1.58 times compared to previously reported experimental results;

4. The capabilities of LED-pumped neodymium-doped crystals, specifically Nd:KGW, were evaluated through a simulation study. The results indicate that Nd:KGW outperforms Nd:YAG in terms of absorption efficiency (66.2% and 37.1%, respectively) and demonstrates a higher slope efficiency (17.9% and 12.1%, respectively). Due to the shorter fluorescence lifetime and lower quantum yield of Nd:KGW, its threshold pump power was higher. However, this value remains close to that of Nd:YAG, suggesting high-power LED-pumped Nd:KGW lasers are achievable;

5. The influence of temperature-dependent spectral shift of LED emission on the absorption characteristics of the active medium was numerically investigated. It is found that with a spectral shift of blue LED emission of 3-5 nm, the absorption efficiency decreases by more than 5%;

6. Ce:Nd:YAG lasers with transverse pumping scheme using blue LEDs were investigated based on simulation models using the Monte Carlo photon tracing technique. The research results demonstrated the possibility of achieving an output power of more than 30 W with 10% optical-to-optical efficiency for the Ce:Nd:YAG laser.

НАУЧНЫЙ СОВЕТ PhD.03/30.09.2020.FM.55.04 ПО ПРИСУЖДЕНИЮ УЧЕНОЙ СТЕПЕНИ ПРИ УРГЕНЧСКОМ ГОСУДАРСТВЕННОМ УНИВЕРСИТЕТЕ ИМЕНИ АБУ РАЙХАНА БЕРУНИ

ИНСТИТУТ ИОННО-ПЛАЗМЕННЫХ И ЛАЗЕРНЫХ ТЕХНОЛОГИЙ

ШЕРМАТОВА ФЕРУЗА АБДУРАШИД КИЗИ

# НЕОДИМОВЫЕ ЛАЗЕРЫ СО СВЕТОДИОДНОЙ НАКАЧКОЙ

**01.04.11- Лазерная физика**

**АВТОРЕФЕРАТ**
**диссертации доктора философии (PhD) по физико-математическим наукам**

**Ургенч – 2025**

**Тема диссертации доктора философии (PhD) зарегистрирована в Высшей аттестационной комиссии при Министерстве высшего образования, науки и инноваций Республики Узбекистан за B2024.3.PhD/FM1163.**

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Защита диссертации состоится «15» Мая 2025 года в 14⁰⁰ часов на заседании Научного совета PhD.03/30.09.2020.FM.55.04 по присуждению ученых степеней при Ургенчском государственном университете. (Адрес: 220100, г. Ургенч, ул. Х. Алимджана, дом 14. Тел.: (99862)224-66-11, факс: (99862) 224-67-00.)

С диссертацией можно ознакомиться в Информационно-ресурсном центре Ургенчского государственного университета (зарегистрирована за №737 (Адрес: 220100, г. Ургенч, ул. Х.Алимджана, дом 14. Тел.: (99862) 224-66-11, факс: (99862) 224-67-00).

Автореферат диссертации разослан «7» 05 2025 года.
(Реестр протокола рассылки 5 от «7» 05 2025 года).

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## ВВЕДЕНИЕ (аннотация диссертации доктора философии (PhD))

**Целью исследования** является выявление основных факторов, препятствующих повышению эффективности преобразования светодиодной энергии в энергию лазерного излучения в условиях непосредственной накачки и предложение решений для разработки и создания высокоэффективных лазерных устройств на основе неодимовых лазерных кристаллов.

**Объект исследования**: светодиоды, твердотельные неодимовые лазерные активные среды, сенсибилизаторы и разные конфигурации лазерных квантронов.

**Предмет исследования**: физические процессы взаимодействия фотонов с лазерной активной средой, сенсибилизатором, поглощение фотонов, люминесценция, передача энергии из ионов сенсибилизаторов в ионы активной среды, процесс лазерного излучения в различных активных средах при светодиодной накачке.

**Научная новизна исследования** заключается в следующем:

предложен новый подход для моделирования процесса излучения светодиодов, позволяющий учёт пространственных и спектральных параметров светодиодных устройств непосредственно из их технического описания;

впервые разработаны симуляционные модели для лазеров со светодиодной накачкой на основе трассировки фотонов Монте-Карло;

на основе результатов моделирования было определено, что лазерные квантроны с изогнутой поверхностью превосходят квантроны с плоской поверхностью по эффективности поглощения и передачи энергии на 5–6% в лазерных системах со светодиодной накачкой;

выявлено, что лазерный стержень Nd:KGW имеет высокий потенциал по сравнению с Nd:YAG в лазерных системах со светодиодной накачкой;

определено, что температурно-зависимый спектральный сдвиг в излучении светодиода влияет на поглощательные свойства лазерной активной среды, в частности, эффективность поглощения снижается более чем на 5% в результате спектрального сдвига на 3-5 нм;

на основе результатов симуляций было выявлено, 10% оптической эффективности преобразования и более 30 Вт выходной лазерной мощности могут быть достигнуты в Ce:Nd:YAG лазерной системе при поперечной накачке синими светодиодами.

**Внедрение результатов исследования.** Результаты исследования, проведенных по изучению поглощения, тепловых свойств и характеристик лазерного излучения в активных средах Nd:YAG, Ce:Nd:YAG и Nd:KGW при светодиодной накачке, были применены в следующих научно-исследовательских проектах:

для разработки компьютерной модели углеродных нанотрубок была использована в фундаментальных исследованиях по бюджетной теме «Моделирование процессов рассеяния, адсорбции и инкапсуляции атомов углеродными наноструктурами и теоретическое исследование упругого рассеяния электронов сферическими фуллеренами», выполненном в Институте ионно-плазменных и лазерных технологий имени У.А. Арифова (Справка 2/1255-2798 академии Наук Республики Узбекистан от 17 декабря 2024 года). Использование полученных результатов позволило оценить влияние температуры на рассеяние атомов в углеродных нанотрубках;

впервые разработанные на основе метода Монте-Карло алгоритмы оптимизации последовательности доменов для генерации третьих гармоник в кристаллах с неоднородной доменной структурой были использованы в проекте Узб-Инд-2021-96 «Разработка методов получения источников многоцветных сверхкоротких лазерных импульсов за счет параметрического воздействия фемтосекундных лазерных импульсов в нелинейных фотонных кристаллах», реализованном в Ташкентском государственном техническом университете (Справка 01/9-14-1717 Ташкентского государственного технического университета от 11 октября 2024 года). Применение результатов предоставило важную информацию о параметрическом усилении коротких лазерных импульсов в нелинейных фотонных кристаллах, что, в свою очередь, позволило разработать инновационные методы оптимизации.

**Структура и объем диссертации**. Диссертация состоит из введения, четырех глав, заключения и списка литературы включая 43 рисунка и 6 таблиц. Текст диссертации изложен на 104 страницах.

## E'LON QILINGAN ISHLAR RO'YXATI

## LIST OF PUBLISHED WORKS

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