Oznaka poročila: ARRS-RPROJ-ZP-2014/38

ZAKLJUČNO POROČILO RAZISKOVALNEGA PROJEKTA

A. PODATKI O RAZISKOVALNEM PROJEKTU

1.Osnovni podatki o raziskovalnem projektu

Šifra projekta	J1-3612
Naslov projekta	Optični mikroresonatorji na osnovi tekočih kristalov
Vodja projekta	9089 Igor Muševič
Tip projekta	J Temeljni projekt
Obseg raziskovalnih ur	7563
Cenovni razred	C
Trajanje projekta	05.2010 - 04.2013
Nosilna raziskovalna organizacija	1554 Univerza v Ljubljani, Fakulteta za matematiko in fiziko
Raziskovalne organizacije - soizvajalke	106 Institut "Jožef Stefan"
Raziskovalno področje po šifrantu ARRS	1 NARAVOSLOVJE 1.02 Fizika 1.02.01 Fizika kondenzirane materije
Družbeno-ekonomski cilj	06. Industrijska proizvodnja in tehnologija
Raziskovalno področje po šifrantu FOS	1 Naravoslovne vede 1.03 Fizika

B. REZULTATI IN DOSEŽKI RAZISKOVALNEGA PROJEKTA

2.Povzetek raziskovalnega projekta[1]

SLO

V okviru projekta smo raziskali možnosti združevanja samourejevalnih lastnosti koloidnih struktur v tekočih kristalih z izjemnimi elektrooptičnimi lastnostmi tekočekristalnih mikroresonatorjev in tako ustvarili temelje za samourejena optična vezja za procesiranje optičnih signalov. Rezultate raziskovalnega projekta lahko strnemo v tri vsebinske sklope, oziroma tri pomembne dosežke. Prvič, dosegli smo bistven napredek pri razumevanju samoorganiziranja nematskih koloidov in disperzij, saj smo odkrili vozlanje in spletanje koloidnih delcev s poljem urejenosti kiralnega nematika. Odkritje vozlov in spletov je bilo objavljeno v reviji Science leta 2011 in pomeni preboj znanosti o tekočih kristalih na področje topologije. Odkritje ima poleg temeljnega pomena tudi močno uporabno vrednost, saj z vozli in spleti lahko mehansko povežemo trdne ali tekoče gradnike v trdno in funkcionalno celoto, to je integrirano vezje iz mehke snovi. Drugi pomemben dosežek je odkritje barvilnega sunkovnega mikrolaserja na osnovi holesterinskega tekočega kristala, objavljeno leta 2010 v reviji Optics Express. Mikrolaser sestavlja mikrometrska kapljica tekočega kristala, znotraj katere se tekoči kristal spontano uredi v optično strukturo, ki predstavlja Braggov-čebulni mikroresonator. Takšen mikrolaser vzbujamo z zunanjo svetlobo in seva nanosekundne svetlobne sunke, ki jih lahko ujamemo in usmerjamo v svetlobne vodnike. Kot takšen torej predstavlja svetlobni sunkovni mikro-izvor na osnovi kompleksne tekočine, v katerem svetlobne impulze uravnavamo s svetlobo. Tretji pomemben dosežek je odkritje svetlobnih valovodov na osnovi smektičnih tekočih kristalov, v katerih smo pokazali tudi stimulirano sevanje svetlobe. Rezultati projekta dokazujejo, da je zares mogoče izdelati posamezne fotonske mikroelemente izključno iz različnih, med seboj nezmesljivih tekočin. Takšne elemente je mogoče topološko zavozlati v trdno celoto, med posameznimi elementi pa lahko resonančno prehaja svetloba, kot smo pokazali v članku v reviji Optics Express leta 2013. S tem smo postavili temelje novi veji v fotoniki, ki jo imenujemo "topološka fotonika". Temelji na samo-organizirani mehki snovi, v kateri je pomembna topologija strukture snovi in po kateri bo mogoče tok fotonov uravnavati s fotoni. Rezultati projekta so bili objavljeni v številnih člankih, ki so dosegli veliko odmevnost. O rezultatih projekta so poročali v nekaterih pomembnih revijah, kot je na primer Nature Photonics, vzbudili pa smo tudi pozornost Optical Society of America, ki je poročala o našem odkritju 3D mikrolaserja in svetlobnih vodnikih iz smektičnega tekočega kristala. Mikrolaser na osnovi tekočih kristalov je v postopku patentne zaščite v večjem številu držav. Rezultati projekta so bili predstavljeni na številnih vabljenih in plenarnih predavanj na mednarodnih konferencah. Na osnovi projekta je pripravljena mednarodna projektna prijava na razpis "Future and Emerging Technologies" v okviru programa Horizon 2020.

ANG

This project combines investigations of the nature of self-organization of nematic liquid crystal colloids and dispersions, with fascinating photonic properties of liquid crystals to create a new platform for self-assembled and integrated micro-photonics. The major results of the project can be summarized into three distinct achievements. First, we have achieved a substantial breakthrough in the field of colloidal self-assembly in nematic liquid crystals by our discovery of knotting and linking of colloidal particles in chiral nematic ordering field. The work was published in Science in 2011 and presents a breakthrough in liquid crystal science towards the mathematical discipline of topology. Besides having a deep fundamental aspect, our work on knots and links in chiral nematic colloids is very important from the point of application of these materials. Knots and links could provide a firm mechanical binding mechanism that could hold colloidal particles and droplets into thermodynamically stable functional unit, i.e. an integrated soft matter photonic circuit. Second important is our demonstration of an optically pumped dye micro-laser, based on a micro-droplet of a chiral nematic liquid crystal, published in Optics Express in 2010. The micro-laser is self-assembled in a form of a small droplet of a chiral nematic liquid crystal, which self-assembles into a structure that is optically equivalent to the Bragg-onion 3D micro-resonator. This laser is excited by external light pulses and emits nano-second light pulses, which can be captured and guided into optical fibres. This laser is a micro-source of coherent and monochromatic light pulses, which is controlled all-optically. The third important result is our demonstration of wave-guiding and lasing in optical micro-fibres made of smectic-A liquid crystal. All these results demonstrate that it is indeed possible to create basic photonic micro-elements based exclusively on different soft matter, i.e. liquid crystals and other immiscible fluids. These photonic elements could be knotted and linked with additional immiscible nematic liquid crystal into firmly bound 3D complex structure, where light could resonantly be transferred between different elements. Successful completion of this project has laid foundations of a novel direction in photonics, named "topological photonics". It is based on self-organized soft matter, where the topology is important and flow of photons is controlled by photons. The results of this project have been published in a large number of articles and have achieved good international visibility. For example, Nature Photonics and Optical Society of America have reported on our publication of 3D micro-laser as well as on lasing article in 2013. We have filled an international patent on 3D micro-laser in several countries worldwide. The results of this project have as well been presented as plenary and invited lectures on several international conferences and universities.

3.Poročilo o realizaciji predloženega programa dela na raziskovalnem projektu[2]

V okviru prvega delovnega sklopa smo raziskali fiziko samo-urejanja koloidnih delcev v nematskem tekočem kristalu in/ali krogelnih nematskih mikroresonatorjev v bližini planarnih ali vlaknastih optičnih valovodov. V okviru tega sklopa smo uspešno opravili naslednje raziskave:

- Izvedene so bile obširne študije spletanja topoloških defektnih linij s koloidnimi delci v kiralnem nematskem tekočem kristalu. Bogatstvo topoloških struktur v kiralnih nematskih koloidih je izjemno veliko, odkrili smo vozle in splete. Raziskave tekočekristalnih koloidov smo v zadnjem letu usmerili še v spletanje in vozlanje cilindričnih in kroglastih objektov v kiralnem nematskem tekočem kristalu. Obetamo si, da bo vozle in splete mogoče uporabiti pri sestavljanju fotonskih mikrovezij na osnovi kiralnih nematskih koloidov. S tega področja smo objavili članek v Science (Tkalec et al., Reconfigurable knots and links in chiral nematic colloids, Science 333, 62(2011)) in Phys. Rev. E 84, 031703(2011).
- Izvedena je bila teoretska študija mehanizmov rekonfiguriranja topoloških zank v nematskih koloidih. V tem delu smo uporabili Landau-de Gennesovo analizo stabilnosti in tehniko lokalne tetrahedrične rotacije za analizo možnih sprememb topologije zank. S tega področja smo objavili članek v reviji Soft Matter 33, 8595 (2012) z naslovom “Stability and rewiring of nematic braids in chiral nematic colloids«, članek z naslovom »Light induced rewiring and wiring of Saturn ring defects in photosensitive chiral nematic colloids« je bil objavljen v EPJ E 36, 97-1-8(2013).
- Uspešno so bile izvedene izjemno obširne raziskave laserske manipulacije in sestavljanja 3D nematskih koloidnih kristalov. Kristal je bil napovedan na osnovi Landau-de Gennesove analize stabilnosti različnih kristalnih koloidnih struktur, po večletnem delu nam je uspelo sestaviti prvi 3D nematski koloidni kristal s približno nekaj več kot 100 delci. Kristal ima tetragonalno strukturo z bazo, v zunanjem električnem polju smo izmerili 30% elektro-strikcijo. V primeru negativne dielektrične anizotropije se kristal kot celota zavrti, kar je presenetljiva snovna lastnost. Članek je bil objavljen v Nature Communications 4, 1489 (2013).
- Opravili smo raziskave topologije nematskih defektnih zank na optičnih vlaknih. Na dolgih vlaknih je eksperiment pokazal presenetljiv rezultat, saj pri hitrem lokalnem ohlajanju tekočega kristala iz izotropne faze iz množice prepletenih defektnih zank

dobimo par ali večje število parov defektnih zank, ki objemajo vlakno. Izvedli smo obširno študijo mehanizmov topološke prepletenosti mikrokroglic in mikrocilindrov, ki je pokazala, da je mogoče topološko pripeti poljubno število mikroresonatorjev na nosilno optično vlakno. Ti rezultati so pomembni in potrjujejo našo začetno hipotezo, na kateri sloni celoten projekt, da je mogoče tvoriti prepletene nematske koloidne strukture za procesiranje optičnih signalov. Članek s to tematiko je bil poslan v objavo.

- V sodelovanju s skupino za sintezo materialov K8 na IJS smo opravili zelo obsežne raziskave oplaščanja kapljic tekočega kristala s silikatnim plaščem debeline nekaj 10 nm. Raziskave so privedle do postopka oplaščanja nematskih kapljic v vodi s tanko plastjo slikata, v pripravi sta patent in publikacija.
- raziskovali smo interakcije med koloidnimi delci v nematskem tekočem kristalu v nanometrskem področju. Določili smo spodnjo mejo velikosti delcev iz SiO_2, ki še posreduje znatno (reda kT) interakcijo, ki je pri premeru 30 nm. Članek s tematiko interakcij med nematskimi koloidnimi delci je bil objavljen v Physical Review E 87, 032501 (2013).
- raziskovali smo koloidne interakcije v kromonskih tekočih kristalih. Ti kristali temeljijo na vodnih raztopinah kromolina (paličasti agregati organskih molekul) in so po svoji naravi sorodni liotropnim nematikom. Raziskave so pokazale spontano zavito notranjo strukturo kromonske kapljice, ki ima zanimive optične lastnosti. Članek je v postopku recenzije v Physical Review E.

Cilji drugega delovnega sklopa so bili raziskati mehanizme resonančnega transporta svetlobe med planarnimi optičnimi valovodi in nematskim mikroresonatorji. Ta delovni sklop je po svoji pomembnosti drugi najbolj obsežen in je usmerjen v razumevanje toka svetlobe v topološko kompleksni mehki snovi:

- razvili smo postopke izdelave planarnih valovodov na osnovi polimerov z visokim lomnim količnikom (1.8 in več) na steklu. Razvili smo metodo "prism-coupler" za sklopitev belega laserskega žarka iz zunanjega superkontinuumskega laserskega izvora. Razvili smo eksperimentalno postavitev za merjenje spektra svetlobe, ki iz planarnega valovoda prehaja v nematski mikroresonator, pri čemer je prostor med valovodom in mikroresonatorjem izpolnjen z vodo. Uspešno smo opravili obsežen sklop meritev prehoda svetlobe iz valovoda v nematski mikroresonator, in ugotovili, da svetloba tunelira pri točno določenih "Whispering Galery Mode" resonancah v kapljici. Opravljena je bila numerična analiza sklopitve elektromagnetnega valovanja v planarnem valovodu in WGM resonancami. Raziskavo smo objavili "Resonant transport of light from planar polymer waveguide into liquid-crystal microcavity", Optics Express 21, 20506-20516(2013), in poročali v okviru predavanja na veliki konferenci SPIE Photonics West, Emerging liquid crstal technologies VIII : 5-6 Februar 2013, San Francisco.

- V sodelovanju z dr. Miho Ravnikom je bila razvita numerična metoda za študij širjenja svetlobe po topoloških nematskih disperzijah na osnovi metode končnih diferenc v časovni domeni (FDTD). V FDTD pristopu se električna in magnetna polja svetlobe prostorsko diskretizira na mrežo, nato pa se jih časovno razvija po mreži v skladu z Maxwellovimi enačbami, kar neposredno modelira tok svetlobe. Zunanji svetlobni viri so modelirani kot robni pogoji, okoliški prostor z absorpcijskimi robnimi pogoji, fluorescenco in lasersko emisijo pa s koreliranimi in lokaliziranimi svetlobnimi izvori. Prednost pristopa je upoštevanja polne modulacije dvolomnosti po prostoru. S to metodo smo uspešno modelirali tok fotonov po smektičnem vlaknu, članek je v pripravi.

- Osredotočili smo se na metode hitre optične modulacije na osnovi STED pojava, ki se uporablja v optični mikroskopiji (STimulated Emission Depletion). Metoda temelji na inhibiciji spontane fluorescence v barvilnih molekulah z uporabo dveh sinhroniziranih optičnih impulzov, pri čemer s prvim impulzov vzbudimo elektronska stanja v fluorescenčnih molekulah, z drugim impulzom pa s stimuliranim sevanjem usmerimo svetlobo izven smeri propagacije vzbujevalne svetlobe. Postavili smo eksperiment in opravili preliminarne meritve, ki kažejo možnost uravnavanja svetlobe s svetlobo z odzivnimi časi v področju pod 1 nanosekundo.

V okviru tretjega večjega sklopa smo raziskali možnosti stimulirane emisije svetlobe v nematskih holesterinskih in smektičnih mikroresonatorjih, dopiranih z laserskimi barvili:

- Raziskovali smo optične lastnosti mikokapljic holesterinskega tekočega kristala, v katerem je lomni kvocient periodično moduliran v radialni smeri. Rezultat je vijačno moduliran tenzor dielektrične konstante, ki kaže optični prepovedan pas in se obnaša kot 1D radialni Braggov reflektor. Pri optičnemu črpanju z zunanjim pulznim laserjem smo ugotovili, da začne mikrokapljica stimulirano oddajati koherentno lasersko svetlobo z zelo ozko spektralno širino pod 0.1 nm. Sevanje je enakomerno v vseh smereh, kar je potrditev napovedi o 3D stimulirani emisiji laserske svetlobe iz optičnih mikroresonatorjev s čebulno strukturo. Članek "3D microlasers from self-assembled cholesteric liquid-crystal microdroplets" smo objavili v Optics Express 18, 26995(2010) in je že v fazi recenzije vzbudil pozornost urednikov. Ti so predlagali in Optical Society of America je dne 8. decembra 2010 izdala tiskovno sporočilo, v katerem je objavila, da so znanstveniki iz Slovenije izdelali prvi 3D mikrolaser na osnovi tekočih kristalov. Sporočilo je dobilo izjemen medijski odziv, saj so nam v januarju 2011 iz OSA sporočili, da je njihovo tiskovno sporočilo doseglo več kot 35 milijonov ljudi po celem svetu. Laser je patentiran s svetovnim patentom.

- Opravili smo obsežne raziskave stimulirane emisije svetlobe v nematskih mikroresonatorjih dopiranih s fluorescenčnimi barvili. Mikroresonatorji so bili dispergirani v vodnem mediju, v katerega smo dodajali molekule različnih surfaktantov, ki vplivajo na površinsko sidranje nematskega tekočega kristala. Posebej obsežne meritve so bile narejene s surfaktantom SDS, ki v večjih koncentracijah povzroči spremembo iz pravokotnega na paralelno sidranje, kar pomeni, da se nematska struktura spremeni iz radialne v bipolarno. Ugotovili smo, da je stimulirana emisija opazna v obeh strukturah, pojavi pa se tudi značilni razcep in premik laserskih črt. Članek je bil objavljen v M.Humar, I.Muševič, Surfactant sensing based on whispering-gallery-mode lasing in liquid-crystal microdroplets. Optics Express 19, 19836(2011).

- Poleg krogelnih resonatorjev, ki jih tvorijo nematski tekoči kristali, smo odkrili rast vlakenskih resonatorjev, ki jih tvorijo nekateri smektični A tekoči kristali ob stiku z vodo in dodatkom detergenta CTAB. Raziskave so bile opravljene v sodelovanju s skupino prof. S. Herminghausa iz Max Planck Institute for Dynamics and Self Organization (MPIDS), Goettingen, Nemčija. Vlakna so enakomerno debela, močno dvolomna in imajo topološki linijski defekt v sredici. Vlakna delujejo kot viskokvalitetni valovodi, krajišča so oblikovana kot idealne sferične leče in so cilindrični mikroresonatorji, v katerih obstajajo "whispering gallery" nihajni načini. Pri optičnem vzbujanju oddajajo lasersko svetlobo pri nizki vzbujevalni moči. Članek z naslovom "Lasing and waveguiding in smectic A liquid crystal optical fibers". smo objavili v reviji Optics Express 21, 30233 (2013). Optical Society of America (OSA) je uvrstila ta članek na portal "Spotlight on Optics" za december 2013, http://www.opticsinfobase.org/spotlight/, ki izpostavlja nekaj izbranih člankov iz vseh publikacij OSA za izbrani mesec. Novico je povzela tudi revija Nature Photonics februarja 2014.

Poleg tega smo raziskali pojav fleksoelektičnosti in ureditvene električnosti v nematskih mikrokapljicah. Pokazali smo, da lahko pride do deformacijsko induciranih potencialov nekaj voltov na mikron, kar že zadošča za izrazite spremembe v stabilnosti defektnih struktur v kapljici. Tako veliki električni potenciali lahko znatno vplivajo na električno uglaševanje mikroresonatorjev. Članek s to tematiko je bil objavljen v Soft Matter, 7, 132 (2011). V okviru raziskav lupinskih resonatorjev smo obravnavali termodinamsko stabilnost različnih lupinastih struktur mikrokapljice, napolnjene s holestrinskim tekočim kristalom z vzporednim površinskim sidranjem molekul tekočega kristala. Izračunane so bile tri stabilne strukture, članek je bil objavljen v Soft Matter. V eksperimentalnih raziskavah smo raziskovali obseg električnega uglaševanja laserskega sevanja iz holesterinske mikrokapljice. Izmerili smo zvezno spreminjanje izsevane valovne dolžine proti modremu delu spektra, največji premik pa je reda 20 nm. Rezultati se trenutno obdelujejo in primerjajo s teoretičnimi napovedmi. V sodelovanju s skupino za ultra-hitro optični spektroskopijo Prof. Th.Rasinga iz Radbout University v Nijmegenu na Nizozemskem smo opravili prve meritve odziva nematskega tekočega kristala na femtosekundne optične impulze iz Ti:safirjevega sunkovnega laserja. Ugotovili smo presenetljivo hiter odziv nematskega tekočega kristala, saj smo izmerili, da se lomni količnik tekočega kristala spremeni za približno 2% v času 200 fs. Na pikosekundni časovni skali je bil opažen še znatni optični odziv, kar obeta izjemno zanimive fizikalne raziskave. Te bodo v prihodnje potekale tudi na IJS, kjer smo poleti 2013 postavili pikosekundni sunkovni laser EXPLA.

4. Ocena stopnje realizacije programa dela na raziskovalnem projektu in zastavljenih raziskovalnih ciljev[3]

Ocenjujemo, da je bil projekt v celoti in uspešno realiziran. Na nekaterih segmentih je bilo doseženo znatno več, kot je bilo predvideno v predlogu projekta, na segmentu dinamike prenosa svetlobe med mikroresonatorji je bilo doseženo nekoliko manj, kar je predvsem posledica eksperimentalnih težav pri izvajanju raziskav v tujini. Dosežena je bila potrditev hipoteze, da je mogoče in mehke snovi izdelati vse potrebne fotonske elemente, iz nih sestaviti s pomočjo topološke vezave kompleksne fotonske strukture, pokazali pa smo tudi, da je mogoč resonančni prenos svetlobe med posameznimi elementi.

5. Utemeljitev morebitnih sprememb programa raziskovalnega projekta oziroma sprememb, povečanja ali zmanjšanja sestave projektne skupine[4]

Med izvajanjem projekta ni bilo bistvenih sprememb raziskovalnega programa ali projektne skupine.

6. Najpomembnejši znanstveni rezultati projektne skupine[5]

	Znanstveni dosežek			
1.	COBISS ID		24377895	Vir: COBISS.SI
	Naslov	*SLO*	3D mikrolaser iz samo-sestavljivega holesterinskega tekočega kristala	

		ANG	3D microlasers from self-assembled cholesteric liquid-crystal microdroplets	
	Opis	SLO	Poročamo o nastavljivem mikrolaserju, ki seva lasersko svetlobo v vse smeri, in je sestavljen v obliki mikro-kapljice holesterinskega tekočega kristala, dopiranega z laserskim barvilom. Holesterik tvori Braggov čebulni optični mikroresonator, enakomerno sevanje laserske svetlobe v 3D prostorski kot pa je posledica stimuliranega sevanje barvilnih molekul v tekočem kristalu. Valovna dolžina sevanja je odvisna izključno od lastne periode vijačnice holesterinske strukture in jo lahko spreminjamo s temperaturo. Milijone enakih mikrolaserjev naredimo s preprostim mešanjem tekočega kristala v nezmesljivi tekočini, kar omogoča preprosto izdelavo laserskih mikro-izvorov za uporabo v integrirani fotoniki.	
		ANG	We demonstrate a tunable and omnidirectional microlaser in the form of a microdroplet of a dye-doped, cholesteric liquid crystal in a carrier fluid. The cholesteric forms a Bragg-onion optical microcavity and the omnidirectional 3D lasing is due to the stimulated emission of light from the dye molecules in the liquid crystal. The lasing wavelength depends solely on the natural helical period of the cholesteric and can be tuned by varying the temperature. Millions of microlasers can be formed simply by mixing a liquid crystal, a laser dye and a carrier fluid, thus providing microlasers for soft-matter photonic devices.	
	Objavljeno v		Optical Society of America; Optics express; 2010; Vol. 18, no. 26; str. 26995-27003; Impact Factor: 3.749;Srednja vrednost revije / Medium Category Impact Factor: 1.753; A': 1; WoS: SY; Avtorji / Authors: Humar Matjaž, Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	
2.	COBISS ID		27532583	Vir: COBISS.SI
	Naslov	SLO	Vodenje in stimulirano sevanje svetlobe v smektičnih A tekočekristalnih vlaknih	
		ANG	Lasing and waveguiding in smectic A liquid crystal optical fibers	
	Opis	SLO	Poročamo o novi vrsti optičnih vlaken, ki se samo-sestavijo v obliki smektičnih-A kristalnih mikrotubic pri rasti na stiku vodne raztopine detergenta in smektičnega-A tekočega kristala. Premer vlaken je izjemno enakomeren, vlakna so močno dvolomna. Odlikujejo se po topološki defektni liniji v sredici vlaken, na obeh koncih pa se samo-sestavi. Optična os poteka od sredice vlakna navzven. V članku pokažemo, da so vlakna odlični svetlobni vodniki, prav tako poročamo o stimuliranem sevanju iz "Whisperring Gallery Mode" načinov. Pri teh načinih svetloba resonančno kroži v notranjosti vlakna in prečno na smer osi vlakna. Valovne in sevalne lastnosti vlaken so močno odvisne od polarizacije črpalne svetlobe. Opazili smo izjemno nizek prag za stimulirano sevanje, ki je pri 75μJ/cm2, ko je črpalna svetloba polarizirana pravokotno na smer orientacije barvilnih molekul. Smektična A vlakna so mehka in lahko gibljiva, z lasersko pinceto jih zlahka manipuliramo, kar obeta nove in zanimive možnosti uporabe v integrirani fotoniki.	
		ANG	We demonstrate a new class of soft matter optical fibers, which are self-assembled in a form of smectic-A liquid crystal microtubes grown in an aqueous surfactant dispersion of a smectic-A liquid crystal. The diameter of the fibers is highly uniform and the fibers are highly birefringent. They are characterized by a line topological defect in the core of the fiber with an optical axis pointing from the defect core towards the surface. We demonstrate guiding of light along the fiber and Whispering Gallery Mode (WGM) lasing in a plane perpendicular to the fiber. The light guiding as well as the lasing threshold are significantly dependent on the polarization of the excitation beam. The observed threshold for WGM lasing is very low (≈ 75μJ/cm2) when the pump beam polarization is perpendicular to the direction of the laser dye alignment and is similar to the lasing threshold in	

			nematic droplets. The smectic-A fibers are soft and flexible and can be manipulated with laser tweezers demonstrating a promising approach for realization of soft photonic circuits.	
	Objavljeno v		Optical Society of America; Optics express; 2013; Vol. 21, no. 25; str. 30233-30242; Impact Factor: 3.546;Srednja vrednost revije / Medium Category Impact Factor: 1.857; A': 1; WoS: SY; Avtorji / Authors: Peddireddy Karthik, Jampani Venkata Subba R., Thutupalli Shashi, Herminghaus Stephan, Bahr Christian, Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	
3.	COBISS ID		2577252	Vir: COBISS.SI
	Naslov	SLO	Resonančni prenos svetlobe med planarnim valovodom in tekočekristalnim mikroresonatorjem	
		ANG	Resonant transport of light from planar polymer waveguide into liquid-crystal microcavity	
	Opis	SLO	Poročamo o resonančnemu prenosu svetlobe iz planarnega valovoda v nematsko mikrokapljico v vodi nad valovodom. Belo svetlobo iz superkontinuumskega laserja vodimo v polimerni planarni valovod s pomočjo prizme. Valovod je v stiku z vodno disperzijo mikrokapljic nematskega tekočega kristala 5CB. Evanescenčno polje svetlobe v valovodu se sklopi z "whispering-gallery-mode" resonancami v 5 − 20μm velikih nematskih kapljicah, ki plavajo v tesni bližini površine valovoda. Opazimo resonančni prenos svetlobe v mikrokapljice, ki se spereminja s temperaturo. Rezultate meritev primerjamo z numeričnimi izračuni v okviru dveh sklopljenih valovanj.	
		ANG	We demonstrate the resonant transfer of light from a planar waveguide to a nematic liquid-crystal microdroplet immersed in water. A wide spectrum of light from a supercontinuum laser source is coupled into a high-refractive-index polymer waveguide using a prism-film coupler. The waveguide is in contact with a water dispersion of droplets from the nematic liquid-crystal 5CB. The evanescent field of the light in the waveguide is resonantly coupled to the whispering-gallery mode resonances, sustained by 5 − 20μm-sized nematic liquid-crystal droplets, which are in close proximity to the waveguide. The resonant transfer of light is tuned by the temperature-induced shifting of the WGM resonances due to the temperature dependence of the refractive index of the nematic liquid crystal. The measurements are compared to the calculations of the coupled-mode	
	Objavljeno v		Optical Society of America; Optics express; 2013; Vol. 21, iss. 18; str. 20506-20516; Impact Factor: 3.546;Srednja vrednost revije / Medium Category Impact Factor: 1.857; A': 1; WoS: SY; Avtorji / Authors: Jampani Venkata Subba R., Humar Matjaž, Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	
4.	COBISS ID		2336868	Vir: COBISS.SI
	Naslov	SLO	Spremenljivi vozli in spleti v kiralnih nematskih koloidih	
		ANG	Reconfigurable knots and links in chiral nematic colloids	
	Opis	SLO	V članku poročamo o vozlih in spletih, ki smo jih opazili in teoretsko pojasnili v koloidni mešanici tekočih kristalov in mikroskopsko majhnih steklenih kroglic. Ugotovili smo, da se v teh mešanicah spontano tvorijo defektne zanke, ki so bodisi zavozlane v vozle ali spletene v različne splete. Uporabili smo lasersko pinceto, da smo analizirali strukturo teh mikroskopsko majhnih vozlov in spletov, prav tako pa smo tudi spreminjali njihovo strukturo s pomočjo laserskega žarka. S teoretičnimi prijemi, ki temeljijo na fenomenologiji in topologiji, smo uspeli pojasniti vse opažene strukture kot tudi napovedati, kakšna so lahko zavozlana stanja v še razsežnejših koloidnih strukturah. Ugotovili smo, da je v	

			takšnih koloidnih sistemih mogoče zavozlati poljuben vozel in splesti poljuben splet.	
		ANG	We report the observation of knots and links in the mixture of a chiral nematic liquid crystal and micrometer-sized silica microspheres. We have observed that in these mixtures, topological defect loops spontaneously form knots and links, spanned on the colloidal scaffold. We used the laser tweezers to analyze and rewire knots and links using the effect of a strongly focused laser light. Using the theoretical approach, based on phenomenology and topology, we have explained the formation and stability of colloidal knots and links observed. To our surprise, arbitrary knot and link can be created on a sufficiently large colloidal array.	
	Objavljeno v		American Association for the Advancement of Science; Science; 2011; Vol. 333, issue 6038; str. 62-65; Impact Factor: 31.201;Srednja vrednost revije / Medium Category Impact Factor: 2.271; A'': 1;A': 1; WoS: RO; Avtorji / Authors: Tkalec Uroš, Ravnik Miha, Čopar Simon, Žumer Slobodan, Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	
5.	COBISS ID		26543143	Vir: COBISS.SI
	Naslov	SLO	Sestavljanje in kontrola 3D nematskih dipolarnih koloidnih kristalov	
		ANG	Assembly and control of 3D nematic dipolar colloidal crystals	
	Opis	SLO	V članku pokažemo, da je mogoče s prostorsko in časovno kontrolo topoloških defektov v dipolarnih nematskih koloidih sestaviti 3D koloidne kristale, ki kažejo nekatere nenavadne snovne lastnosti, kot sta gigantska elektrostrikcija in kolektivna elektro-rotacija. 3D koloidne kristale smo sestavili iz 4 mikrometrskih steklenih kroglic s pomočjo laserske pincete in določili natančni protokol, kot ga določajo topološki defekti in topologija celotnega kristala. 3D koloidni kristali imajo tetragonalno simetrijo s paralelnimi topološkimi dipoli in kažejo gigantsko elektrostrikcijo, saj se skrčijo za 25-30% pri električnem polju 0.37V/mikrometer. V primeru uporabe nematskega tekočega kristala znegativno dielektrično anizotropijo zunanje električno polje povzročikolektivno rotacijo kristala s koti zasuka reda 30 stopinj pri polju 0.14V/mikrometer. 3D nematski koloidni kristal predstavlja nov razred električno odzivnih mehkih materialov.	
		ANG	We demonstrate that control over spatial and temporal positioning of topological defects allows for the design and assembly of 3D nematic colloidal crystals, giving some unexpected material properties, such as giant electrostriction and collective electrorotation. Using laser tweezers, we have assembled 3D colloidal crystals made up of 4 micrometer spheres in a bulk nematic liquid crystal, implementing a step-by-step protocol, dictated by the orientation of point defect. The 3D colloidal crystals have tetragonal symmetry with antiparallel topological dipoles and exhibit giant electrostriction, shrinking by 25-30% at 0.37V/micrometer. An external electric field induces a reversible and controllable electrorotation of the crystal as a whole, with the angle of rotation being 30 degrees at 0.14V/micrometer when using liquid crystal with negative dielectric anisotropy. This demonstrates a new class of electrically highly responsive soft materials.	
	Objavljeno v		Nature Publishing Group; Nature communications; 2013; Vol. 4; str. 1489-1-1489-8; Impact Factor: 10.015;Srednja vrednost revije / Medium Category Impact Factor: 2.514; A'': 1;A': 1; WoS: RO; Avtorji / Authors: Nych Andriy, Ognysta Ulyana, Škarabot Miha, Ravnik Miha, Žumer Slobodan, Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	

7.Najpomembnejši družbeno-ekonomski rezultati projektne skupine[6]

	Družbeno-ekonomski dosežek			
1.	COBISS ID		26602791	Vir: COBISS.SI
	Naslov	*SLO*	Nematski koloidi, topologija in fotonika	
		ANG	Nematic colloids, topology and photonics	
	Opis	*SLO*	Na povabilo dr. Susanne Klein sem se udeležil mednarodnega srečanja z naslovom "New frontiers in anisotropic fluid-particle composites" v organizaciji Royal Society v Chicheley Hallu v Veliki Britaniji. Predavanje z naslovom "Topology and liquid crystal colloids" je bilo zelo dobro sprejeto. V okviru srečanja je izšel tudi zbornik predavanj v Philosophical transactions of the Royal Society of London. V mojem prispevku je podan pregled in diskusija razvoja na področju nematskih koloidov s poudarkom na uporabi v fotoniki. Podan je pregled topologije nematskih koloidov, ki je odgovorna za pojav strukturnih sil med koloidnimi delci v tekočem kristalu. Obravnavam razvoj na področju izdelave mikrolaserjev na osnovi tekočih kristalov s poudarkom na holesterinskem 3D mikrolaserju in električno nastavljivih nematskih mikrolaserjih. Topologija in fotonika nematskih disperzij in koloidov predstavljata zanimivo kombinacijo, na osnovi katere bo mogoč znaten razvoj v prihodnosti.	
		ANG	I was invited by Dr. Susanne Klein to give an invited talk at a topical meeting entitled "New frontiers in anisotropic fluid-particle composites" organized by the Royal Society in Chicheley Hall, Great Britain. My lecture, entitled "Topology and liquid crystal colloids" was very well accepted and the corresponding paper was published in Philosophical transactions of the Royal Society of London. We review and discuss recent progress in the field of nematic colloids, with an emphasis on possible future applications in photonics. The role of the topology is described, based on experimental manipulations of the topological defects in nematic colloids. The topology of the ordering field in nematics provides the forces between colloidal particles that are unique to these materials. We also discuss recent progress in the new field of active microphotonic devices based on liquid crystals (LCs), where chiral nematic microlasers and tuneable nematic microresonators are just two of the recently discovered examples. We conclude that the combination of topology and microphotonic devices based on LCs provides an interesting platform for future progress in the field of LCs.	
	Šifra		B.04 Vabljeno predavanje	
	Objavljeno v		Royal Society of London.; Philosophical transactions of the Royal Society of London; 2013; Vol. 371, no. 1988; str. 20120266 1- 20120266-15; Avtorji / Authors: Muševič Igor	
	Tipologija		1.01 Izvirni znanstveni članek	
2.	COBISS ID		26699303	Vir: COBISS.SI
	Naslov	*SLO*	Resonančni prenos svetlobe med planarnim valovodom in nastavljivim tekočekristalnim mikroresonatorjem	
		ANG	Resonant transfer of light from a planar waveguilde into a tunable nematic liquid crstal microcavity	
	Opis	*SLO*	V dneh od 4. do 7. februarja sem se udeležil velike mednarodne konference z naslovom Photonics West, kjer sem v sekciji »Emerging Liquid Crystal Technologies VIII« predstavil vabljeno predavanje z naslovom »Resonant transfer of light from a planar waveguide into a tunable nematic liquid crystal microcavity«. Predavanje je bilo zelo dobro sprejeto. Na povabilo prof. dr. Ivana Smalyukha sem v dneh od 7. do 8. februarja 2013 obiskal Department of Physics na University of Colorado at Boulder. Na univerzi sem imel vabljeno predavanje v okviru serije predavanj »Big Energy seminar series«, kjer sem predstavil naše delo s področja fotonike in	

			topologije v predavanju »Topological soft materials for all-optic low energy photonics«. Predavanje je bilo zelo dobro sprejeto.	
		ANG	I was invited to attend the international conference Photonics West, where I presented an invited paper entitled »Resonant transfer of light from a planar waveguide into a tunable nematic liquid crystal microcavity« within the conference sestion »Emerging Liquid Crystal Technologies VIII«. The lecture was accepted very well and I was also invited by Professor Ivan Smalyukh from the "Department of Physics " at University of Colorado at Boulder to present an invited lecture within the »Big Energy seminar series«. The lecture was entitled »Topological soft materials for all-optic low energy photonics« and I presented an overview of our recent work on photonic devices based on liquid crystals. The lecture was very well accepted.	
	Šifra		B.04 Vabljeno predavanje	
	Objavljeno v		SPIE; Emerging liquid crstal technologies VIII; 2013; Str. 86420E-1-86420E-8; Avtorji / Authors: Jampani Venkata Subba R., Humar Matjaž, Muševič Igor	
	Tipologija		1.06 Objavljeni znanstveni prispevek na konferenci (vabljeno predavanje)	
3.	COBISS ID		24853031	Vir: COBISS.SI
	Naslov	SLO	Direktne in inverzne nematske disperzije za fotoniko iz mehke snovi	
		ANG	Direct and inverted nematic dispersions for soft matter photonics	
	Opis	SLO	Na povabilo organizatorja sem se v dneh od 15. do 21. avgusta 2010 na povabilo prof. Hiroshi Orihare iz Hokkaido University udeležil velikega mednarodnega simpozija "International Symposium on Non-Equilibrium Soft Matter 2010" v Nari na Japonskem. Tema simpozija so bili najnovejši dosežki na področju fizike, kemije in aplikacije mehke snovi. Posebej so bila izpostavljena področja koloidov, biofizike, statistične fizike in tekočih kristalovi. Simpozija so se udeležili vodilni raziskovalci iz vsega sveta, na simpoziju sem predstavil delo naše raziskovalne skupine v vabljenem predavanju z naslovom "Nematic Colloidal Crystals and Superstructures", ki je bilo sprejeto z velikim zanimanjem. Predavanje je bilo objavljeno v posebni številki revije Journal of Physics.	
		ANG	I was invited by Professor Hiroshi Orihara from Hokkaido University, Japan, to attend an international symposium "International Symposium on Non-Equilibrium Soft Matter 2010" that was held in Nara, Japan. The subject of the meeting was cutting edge results from soft-matter phaysics, chemistry and application. Special emphasis was given to colloids, biophysics, statistical physics and liquid crystals. The meeting was attended by world-leading scientists. I presented our work in an invited lecture "Nematic Colloidal Crystals and Superstructures", which was accepted with great interest. This lecture was published in a special edition of Journal of Physics.	
	Šifra		B.04 Vabljeno predavanje	
	Objavljeno v		IOP Publishing; Journal of physics; 2011; Vol. 23, no. 28; str. 284112-1-284112-7; Impact Factor: 2.546;Srednja vrednost revije / Medium Category Impact Factor: 3.579; A': 1; WoS: UK; Avtorji / Authors: Muševič Igor, Škarabot Miha, Humar Matjaž	
	Tipologija		1.02 Pregledni znanstveni članek	
4.	COBISS ID		26597671	Vir: COBISS.SI
	Naslov	SLO	Topologija in samo-organiziranost nematskih koloidov	
		ANG	Topology and Self Assembly of Nematic colloids	
			Na povabilo prof. Claudie Schmidt sem se udeležil mednarodnega srečanja	

	Opis	SLO	z naslovom "46th Biennial Meeting of the Colloid Society" v organizaciji Univerze v Paderbornu. Na srečanju sem imel plenarno predavanje z naslovom "Topology and Self Assembly of Nematic Colloids", ki je bilo zelo dobro sprejeto.	
		ANG	I was invited by Prof. Claudie Schmidt to attend an international meeting entitled "46th Biennial Meeting of the Colloid Society" which was organized by the University of Paderborn. I delivered a plenary lecture entitled "Topology and Self Assembly of Nematic Colloids", which gave an overview of our results on soft matter photonics. The lecture was very well accepted.	
	Šifra		B.04 Vabljeno predavanje	
	Objavljeno v		German Chemical Society; Scientific program; 2012; Avtorji / Authors: Muševič Igor	
	Tipologija		1.10 Objavljeni povzetek znanstvenega prispevka na konferenci (vabljeno predavanje)	
5.	COBISS ID		25561639	Vir: COBISS.SI
	Naslov	SLO	Kroglasti tekočekristalni laser	
		ANG	Spherical liquid-crystal laser	
	Opis	SLO	Izum je kroglasti izvor laserske svetlobe z eno ali več kapljic tekočega kristala. Notranjost je zapolnjena s kiralnim tekočim kristalom in laserskega aktivnega medija, ki se uredi v obliki vijačne strukture. Kapljico osvetljujemo s svetlobo iz zunanjega svetlobnega vira tako, da se nad določeno gostoto svetlobnega toka dobi presežek stimulirano sevane svetlobe nad izgubami. Radialna modulacija lomnega količnika v notranjosti kapljice povzroča Braggove odboje svetlobe, tekočekristalna vijačna struktura zatorej deluje kot radialni Braggov reflektor, kapljica pa tvori radialni optični resonator.	
		ANG	The invention is a spherical source of laser light including one or more droplets of chiral liquid crystals, with the addition of an active laser medium. Due to the chirality, the liquid crystals adopts a helical structure with a periodic variation of the dielectric tensor. The droplet is illuminated, so that an excess of the stimulated light over its loss is gained. The modulation of the refractive index causes a Bragg reflection of the light and the helical liquid crystalline structure functions as a radial Bragg reflector, thus forming an optical Bragg microresonator	
	Šifra		F.33 Patent v Sloveniji	
	Objavljeno v		European Patent Attorneys; 2011; Avtorji / Authors: Muševič Igor, Humar Matjaž	
	Tipologija		2.23 Patentna prijava	

8.Drugi pomembni rezultati projetne skupine[7]

9.Pomen raziskovalnih rezultatov projektne skupine[8]

9.1.Pomen za razvoj znanosti[9]

SLO

V znanstveni sferi velja konsenz, da je znanost o svetlobi tista znanost, ki bo imela eno od najbolj pomembnih vlog v 21. stoletju. Uspešno smo dokončali ambiciozen raziskovalni projekt, ki je v samem vrhu današnje znanosti o svetlobi, koloidih in tekočih kristalih in ki s svojimi novimi rezultati postavlja pomembne temelje za novo smer na področju fotonike. Projekt je prinesel veliko število novih znanstvenih spoznanj, med katerimi naj omenimo tri najbolj pomembne. Dosegli smo velik napredek pri razumevanju samoorganiziranja nematskih koloidov in disperzij, saj smo odkrili vozlanje in spletanje koloidnih delcev s poljem urejenosti kiralnega nematika. Odkritje vozlov in spletov je bilo objavljeno v reviji Science leta 2011 in pomeni preboj znanosti o tekočih kristalih na področje topologije. Odkritje ima poleg temeljnega pomena tudi močno uporabno vrednost, saj vozli in spleti omogočajo mehansko povezavo trdnih ali tekočih gradnikov v trdno in funkcionalno celoto, to je integrirano vezje iz mehke snovi. Pomemben znanstveni dosežek je odkritje barvilnega sunkovnega mikrolaserja na osnovi holesterinskega tekočega kristala, objavljeno leta 2010 v reviji Optics Express. Mikrolaser predstavlja svetlobni sunkovni mikro-izvor na osnovi kompleksne tekočine, v katerem svetlobne impulze uravnavamo s svetlobo in je vzbudil veliko pozornost znanstvene in tehnološke sfere po svetu. Tretji pomemben doprinos k znanosti je odkritje svetlobnih valovodov na osnovi smektičnih tekočih kristalov, v katerih smo pokazali tudi stimulirano sevanje svetlobe. Znanstveni rezultati projekta dokazujejo, da je zares mogoče izdelati posamezne fotonske mikroelemente izključno iz različnih, med seboj nezmesljivih tekočin. Takšne elemente je mogoče topološko zavozlati v trdno celoto, med posameznimi elementi pa lahko resonančno prehaja svetloba. S tem smo postavili temelje novi veji v fotoniki, ki jo imenujemo "topološka fotonika". Temelji na samo-organizirani mehki snovi, v kateri je pomembna topologija strukture snovi in po kateri bo mogoče tok fotonov uravnavati s fotoni. Rezultati projekta so bili objavljeni v številnih člankih, ki so dosegli veliko mednarodno odmevnost. O rezultatih projekta so poročali v nekaterih pomembnih revijah, kot je na primer Nature Photonics, vzbudili pa smo tudi pozornost Optical Society of America, ki je poročala o našem odkritju 3D mikrolaserja in svetlobnih vodnikih iz smektičnega tekočega kristala.

ANG

It is generally accepted in the scientific community, that photonics will be one of the fastest developing scientific disciplines of the 21st century. We have completed an ambitious research project, which is at the cutting edge of today's photonics, colloidal science and liquid crystals that has laid foundations for the new direction in photonics, which may have profound impact in the future. There are several important scientific contributions of this project and among these lat us mention only three most important. We have achieved a substantial breakthrough in the field of colloidal self-assembly in nematic liquid crystals by our discovery of knotting and linking of colloidal particles in chiral nematic ordering field, published in Science in 2011. Besides having a deep fundamental aspect, our work on knots and links is important for application, because knots and links provide a firm mechanical binding of colloidal particles and droplets into thermodynamically stable functional unit, i.e. an integrated soft matter photonic circuit. Our demonstration of an optically pumped dye micro-laser, based on a micro-droplet of a chiral nematic liquid crystal, has attracted huge scientific interest, because it is the first micro-source of coherent and monochromatic light pulses, which is controlled all-optically. The third important result is our demonstration of wave-guiding and lasing in optical micro-fibres made of smectic-A liquid crystal. All these results demonstrate that it is indeed possible to create basic photonic micro-elements based exclusively on different soft matter, i.e. liquid crystals and other immiscible fluids. These photonic elements could be knotted and linked with additional immiscible nematic liquid crystal into firmly bound 3D complex structure, where light could resonantly be transferred between different elements. Successful completion of this project has laid foundations fora novel direction in photonics, named "topological photonics". It is based on self-organized soft matter, where the topology is important and flow of photons is controlled by photons. The results of this project have been published in a large number of articles and have achieved excellent international visibility. For example, Nature Photonics and Optical Society of America have reported on our 3D micro-laser and lasing liquid crystalline fibres.

9.2.Pomen za razvoj Slovenije[10]

SLO

Uspešno zaključen projekt »Optični mikroresonatorji na osnovi tekočih kristalov« je pomembno prispeval k vključitvi dela slovenske znanosti na področje fotonike v svetu. Fotonika je veja fizike, ki doživlja v zadnjih letih izjemno hiter razvoj na zelo različnih področjih, od kvantnega računalništva, preko vse-svetlobne tehnologije procesiranja signalov do zajemanja in pretvorbe energije sonca v obnovljive energetske vire. Projekt predstavlja uspešen doprinos na področju znanosti in tehnologije procesiranja optičnih signalov, po svojih temeljnih dosežkih pa sega tudi

do abstraktne teorije topologije, katere realizacijo smo odkrili v tekočih kristalih. Uspešna izvedba projekta se kaže v naslednjih prispevkih, pomembnih za razvoj znanosti v Sloveniji:
1. Sodelovanje slovenskih znanstvenikov v mednarodnih projektih. Skupini, ki sta projekt izvajali, sta bili tudi po zaslugi tega projekta vključeni v 6 mednarodnih projektov s sorodno tematiko: (1) COST D43 Action Colloid and Interface Chemistry for Nanotechnology, members of WG2 "Synthesis and Availability of Reference Materials" (I. Muševič); (2) COST MP 0604, "Optical micromanipulation by nonlinear photonics", I. Muševic, Slovenian representative; (3) FP7 Marie Curie Initial Training Network "Hierarchical Assembly in Controllable Matrices" s tremi slovenskimi partnerji. (4) NEMCODE- Controlled Assembly and Stabilization of Functionalized Colloids in Nematic Liquid Crystals, Marie Curie podoktorski projekt, ki ga izvaja dr. Giorgio Mirri na Institutu J.Stefan (2013-2015). (5) LIVINGLASER- A laser made entirely of living cells and materials derived from living organisms, Marie Curie podoktorski projekt, ki ga izvaja dr. Matjaž Humar na IJS in General Hospital Corporation, Boston, ZDA. (6) Bilateralni projekt Slovenija-Ukrajina, BI-UA/13-14-007; Modre faze tekočih kristalov.
2. V postopku zaščite je patent »Spherical liquid-crystal laser« in sicer v EU, ZDA, Rusiji, Kitajski, Južni Koreji, Hong Kong, Japonski in Indiji.
3. Izvedena so bila 4 plenarna predavanja na velikih mednarodnih konferencah in sicer na "46th Biennial Meeting of the Colloid Society" v organizaciji Univerze v Paderbornu, "24th International Liquid Crystal Conference" v organizaciji International Liquid Crystal Society, na "8th Liquid Matter Conference" v organizaciji Univerze na Dunaju, "Wetting and Capillarity in Complex Systems" v organizaciji "Max-Planck Institute fur physik komplexe systeme" in »12th International Symposium on Colloidal and Molecular Electrooptics v organizaciji Univerze v Mainzu.
4. Izvedenih je bilo 12 vabljenih predavanj na mednarodnih znanstvenih konferencah.
5. O projektnih rezultatih smo poročali na 6 vabljenih predavanjih na tujih univerzah in sicer University of Oxford, University of Colorado at Boulder, Radboud University, Nijmegen, University of California, Santa Barbara, Univerza La Sapienza, Rim, in Max Planck Institute for Dynamics and Self-Organization, Goettingen, Nemčija.
6. Iz tematike projekta so bili opravljeni tri doktorati in sicer dr. Tkalec Uroš, Institut 'Jožef Stefan', dr. Humar Matjaž, Institut 'Jožef Stefan', in dr. Venkata Subba Rao Jampani, Univerza v Ljubljani, Fakulteta za matematiko in fiziko.

Uspešna izvedba projekta bo pomembno pripomogla pri vključevanju v prihodnje projekte, saj se na osnovi rezultatov pripravlja mednarodna projektna prijava na razpis "Future and Emerging Technologies" v okviru programa Horizon 2020, v letu 2017 pa bo v Ljubljani potekala velika mednarodna konferenca Liquid Matter 2017.

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Our successfully completed project »Optical Microresonators based on Liquid Crystals« has contributed significantly to the international cooperation of Slovenian scientists in the field of Photonics. Photonics is one of the most rapidly evolving fields of Physics and includes such diverse sub-fields, such as quantum computing, all-optic processing of information to harvesting of light for sustainable development. This project has brought some important contributions not only in the applied area of all-optical processing of information, but also experimental realization of fundamental phenomena of topology. Successful completion of this project has several important contributions for Slovenia:

1. Participation of Slovenian scientists in several international projects, related to photonics. Two research groups, which have completed the project, have participated in 6 international scientific projects: (1) COST D43 Action Colloid and Interface Chemistry for Nanotechnology, members of WG2 "Synthesis and Availability of Reference Materials" (I. Muševič); (2) COST MP 0604, "Optical micromanipulation by nonlinear photonics", I. Muševic, Slovenian representative; (3) FP7 Marie Curie Initial Training Network "Hierarchical Assembly in Controllable Matrices" including 3 partners from Slovenia. (4) NEMCODE- Controlled Assembly and Stabilization of Functionalized Colloids in Nematic Liquid Crystals, Marie Curie post-docproject by Dr. Giorgio Mirri at J.Stefan Institute (2013-2015). (5) LIVINGLASER- A laser made entirely of living cells and materials derived from living organisms, Marie Curie post-doc project by Dr. Matjaž Humar at IJS and General Hospital Corporation, Boston, USA. (6) Bilateral project Slovenia-Ukraine, BI-UA/13-14-007; Blue Phases of Liquid Crystals.

2. We have patented our work on 3D microlasers in an PCT application »Spherical liquid-crystal

laser«, which is now in a process of obtaining national patents in several countries of EU, USA, Russia, China, South Korea, Hong Kong, Japan and India.

3. We were invited to give 4 plenary lectures at important international conferences, including "46th Biennial Meeting of the Colloid Society" organized by the University of Paderbornu, "24th International Liquid Crystal Conference" organized by the International Liquid Crystal Society, "8th Liquid Matter Conference" organized by the University of Vienna, "Wetting and Capillarity in Complex Systems" organized by the "Max-Planck Institute fur physik komplexe systeme" and »12th International Symposium on Colloidal and Molecular Electrooptics" organized by the University in Mainzu.

4. We were invited to give 12 invited lectures at international conferences

5. We were invited to give 6 invited lectures at foreign universities, including the University of Oxford, University of Colorado at Boulder, Radboud University, Nijmegen, University of California, Santa Barbara, Univerza La Sapienza, Rim, and Max Planck Institute for Dynamics and Self-Organization, Goettingen, Germany.

6. Three PhD Thesis have been completed within this project, including Dr. Tkalec Uroš, Institut 'Jožef Stefan', Dr. Humar Matjaž, Institut 'Jožef Stefan', and Dr. Venkata Subba Rao Jampani, University of Ljubljani, Faculty of Mathematics and Physics.

Successful completion of this project will help in obtaining new projects in the future, the groups are in a process of preparation of the proposal within "Future and Emerging Technologies" of Horizon 2020; in the year 2017, Ljubljana will host the international scientific conference "Liquid Matter 2017".

10.Samo za aplikativne projekte in podoktorske projekte iz gospodarstva!
Označite, katerega od navedenih ciljev ste si zastavili pri projektu, katere konkretne rezultate ste dosegli in v kakšni meri so doseženi rezultati uporabljeni

Cilj		
F.01	**Pridobitev novih praktičnih znanj, informacij in veščin**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.02	**Pridobitev novih znanstvenih spoznanj**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.03	**Večja usposobljenost raziskovalno-razvojnega osebja**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.04	**Dvig tehnološke ravni**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	

F.05	**Sposobnost za začetek novega tehnološkega razvoja**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.06	**Razvoj novega izdelka**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.07	**Izboljšanje obstoječega izdelka**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.08	**Razvoj in izdelava prototipa**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.09	**Razvoj novega tehnološkega procesa oz. tehnologije**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.10	**Izboljšanje obstoječega tehnološkega procesa oz. tehnologije**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.11	**Razvoj nove storitve**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.12	**Izboljšanje obstoječe storitve**	
	Zastavljen cilj	DA NE
	Rezultat	
	Uporaba rezultatov	
F.13	**Razvoj novih proizvodnih metod in instrumentov oz. proizvodnih procesov**	
	Zastavljen cilj	DA NE
	Rezultat	

	Uporaba rezultatov	
F.14	**Izboljšanje obstoječih proizvodnih metod in instrumentov oz. proizvodnih procesov**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.15	**Razvoj novega informacijskega sistema/podatkovnih baz**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.16	**Izboljšanje obstoječega informacijskega sistema/podatkovnih baz**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.17	**Prenos obstoječih tehnologij, znanj, metod in postopkov v prakso**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.18	**Posredovanje novih znanj neposrednim uporabnikom (seminarji, forumi, konference)**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.19	**Znanje, ki vodi k ustanovitvi novega podjetja ("spin off")**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.20	**Ustanovitev novega podjetja ("spin off")**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.21	**Razvoj novih zdravstvenih/diagnostičnih metod/postopkov**	
	Zastavljen cilj	○ DA ○ NE
	Rezultat	
	Uporaba rezultatov	
F.22	**Izboljšanje obstoječih zdravstvenih/diagnostičnih metod/postopkov**	

	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.23	**Razvoj novih sistemskih, normativnih, programskih in metodoloških rešitev**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.24	**Izboljšanje obstoječih sistemskih, normativnih, programskih in metodoloških rešitev**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.25	**Razvoj novih organizacijskih in upravljavskih rešitev**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.26	**Izboljšanje obstoječih organizacijskih in upravljavskih rešitev**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.27	**Prispevek k ohranjanju/varovanje naravne in kulturne dediščine**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.28	**Priprava/organizacija razstave**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.29	**Prispevek k razvoju nacionalne kulturne identitete**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.30	**Strokovna ocena stanja**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	

	Uporaba rezultatov	
F.31	**Razvoj standardov**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.32	**Mednarodni patent**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.33	**Patent v Sloveniji**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.34	**Svetovalna dejavnost**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	
F.35	**Drugo**	
	Zastavljen cilj	◯ DA ◯ NE
	Rezultat	
	Uporaba rezultatov	

Komentar

11.Samo za aplikativne projekte in podoktorske projekte iz gospodarstva!
Označite potencialne vplive oziroma učinke vaših rezultatov na navedena področja

	Vpliv	**Ni vpliva**	**Majhen vpliv**	**Srednji vpliv**	**Velik vpliv**	
G.01	**Razvoj visokošolskega izobraževanja**					
G.01.01.	Razvoj dodiplomskega izobraževanja	◯	◯	◯	◯	
G.01.02.	Razvoj podiplomskega izobraževanja	◯	◯	◯	◯	
G.01.03.	Drugo:	◯	◯	◯	◯	
G.02	**Gospodarski razvoj**					
G.02.01	Razširitev ponudbe novih izdelkov/storitev na trgu	◯	◯	◯	◯	
G.02.02.	Širitev obstoječih trgov	◯	◯	◯	◯	
G.02.03.	Znižanje stroškov proizvodnje	◯	◯	◯	◯	
	Zmanjšanje porabe materialov in					

G.02.05.	Razširitev področja dejavnosti	◯	◯	◯	◯	
G.02.06.	Večja konkurenčna sposobnost	◯	◯	◯	◯	
G.02.07.	Večji delež izvoza	◯	◯	◯	◯	
G.02.08.	Povečanje dobička	◯	◯	◯	◯	
G.02.09.	Nova delovna mesta	◯	◯	◯	◯	
G.02.10.	Dvig izobrazbene strukture zaposlenih	◯	◯	◯	◯	
G.02.11.	Nov investicijski zagon	◯	◯	◯	◯	
G.02.12.	Drugo:	◯	◯	◯	◯	
G.03	**Tehnološki razvoj**					
G.03.01.	Tehnološka razširitev/posodobitev dejavnosti	◯	◯	◯	◯	
G.03.02.	Tehnološko prestrukturiranje dejavnosti	◯	◯	◯	◯	
G.03.03.	Uvajanje novih tehnologij	◯	◯	◯	◯	
G.03.04.	Drugo:	◯	◯	◯	◯	
G.04	**Družbeni razvoj**					
G.04.01	Dvig kvalitete življenja	◯	◯	◯	◯	
G.04.02.	Izboljšanje vodenja in upravljanja	◯	◯	◯	◯	
G.04.03.	Izboljšanje delovanja administracije in javne uprave	◯	◯	◯	◯	
G.04.04.	Razvoj socialnih dejavnosti	◯	◯	◯	◯	
G.04.05.	Razvoj civilne družbe	◯	◯	◯	◯	
G.04.06.	Drugo:	◯	◯	◯	◯	
G.05.	**Ohranjanje in razvoj nacionalne naravne in kulturne dediščine in identitete**	◯	◯	◯	◯	
G.06.	**Varovanje okolja in trajnostni razvoj**	◯	◯	◯	◯	
G.07	**Razvoj družbene infrastrukture**					
G.07.01.	Informacijsko-komunikacijska infrastruktura	◯	◯	◯	◯	
G.07.02.	Prometna infrastruktura	◯	◯	◯	◯	
G.07.03.	Energetska infrastruktura	◯	◯	◯	◯	
G.07.04.	Drugo:	◯	◯	◯	◯	
G.08.	**Varovanje zdravja in razvoj zdravstvenega varstva**	◯	◯	◯	◯	
G.09.	**Drugo:**	◯	◯	◯	◯	

Komentar

12.Pomen raziskovanja za sofinancerje[11]

	Sofinancer			
1.	Naziv			
	Naslov			
	Vrednost sofinanciranja za celotno obdobje trajanja projekta je znašala:			EUR
	Odstotek od utemeljenih stroškov projekta:			%
	Najpomembnejši rezultati raziskovanja za sofinancerja			Šifra
		1.		
		2.		
		3.		
		4.		
		5.		
	Komentar			
	Ocena			

13.Izjemni dosežek v letu 2013[12]

13.1. Izjemni znanstveni dosežek

V znanstveni reviji Optics Express; 2013; Vol. 21, no. 25; str. 30233-30242, smo objavili članek "Lasing and waveguiding in smectic A liquid crystal optical fibers" (Vodenje in stimulirano sevanje svetlobe v smektičnih A tekočekristalnih vlaknih), avtorjev Peddireddy Karthik, Jampani Venkata Subba R., Thutupalli Shashi, Herminghaus Stephan, Bahr Christian, Muševič Igor, ki je vzbudil posebno zanimanje Optical Society of America (OSA), ki to revijo izdaja. OSA, ki je največje svetovno združenje znanstvenikov s področja optike in fotonike, je uvrstila ta članek na portal "Spotlight on Optics" za december 2013, http://www.opticsinfobase.org/spotlight/. Na tem portalu OSA vsak mesec objavi komentarje, ki so posvečeni nekaj posebej izbranim in izpostavljenim člankom iz velikega števila revij, ki jih izdaja OSA. Uvrstitev na ta portal izmed zelo velikega števila objavljenih člankov iz vsega sveta, pomeni posebno priznanje raziskovalcem iz Slovenije in Nemčije.

13.2. Izjemni družbeno-ekonomski dosežek

C. IZJAVE

Podpisani izjavljam/o, da:

- so vsi podatki, ki jih navajamo v poročilu, resnični in točni
- se strinjamo z obdelavo podatkov v skladu z zakonodajo o varstvu osebnih podatkov za potrebe ocenjevanja ter obdelavo teh podatkov za evidence ARRS
- so vsi podatki v obrazcu v elektronski obliki identični podatkom v obrazcu v pisni obliki
- so z vsebino zaključnega poročila seznanjeni in se strinjajo vsi soizvajalci projekta

Podpisi:

zastopnik oz. pooblaščena oseba raziskovalne organizacije:	in	*vodja raziskovalnega projekta:*
Univerza v Ljubljani, Fakulteta za matematiko in fiziko		Igor Muševič
______________________		______________________

ŽIG

Kraj in datum: | Ljubljana | 10.4.2014

Oznaka prijave: ARRS-RPROJ-ZP-2014/38

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[1] Napišite povzetek raziskovalnega projekta (največ 3.000 znakov v slovenskem in angleškem jeziku) Nazaj

[2] Napišite kratko vsebinsko poročilo, kjer boste predstavili raziskovalno hipotezo in opis raziskovanja. Navedite ključne ugotovitve, znanstvena spoznanja, rezultate in učinke raziskovalnega projekta in njihovo uporabo ter sodelovanje s tujimi partnerji. Največ 12.000 znakov vključno s presledki (približno dve strani, velikost pisave 11). Nazaj

[3] Realizacija raziskovalne hipoteze. Največ 3.000 znakov vključno s presledki (približno pol strani, velikost pisave 11) Nazaj

[4] V primeru bistvenih odstopanj in sprememb od predvidenega programa raziskovalnega projekta, kot je bil zapisan v predlogu raziskovalnega projekta oziroma v primeru sprememb, povečanja ali zmanjšanja sestave projektne skupine v zadnjem letu izvajanja projekta, napišite obrazložitev. V primeru, da sprememb ni bilo, to navedite. Največ 6.000 znakov vključno s presledki (približno ena stran, velikost pisave 11). Nazaj

[5] Navedite znanstvene dosežke, ki so nastali v okviru tega projekta. Raziskovalni dosežek iz obdobja izvajanja projekta (do oddaje zaključnega poročila) vpišete tako, da izpolnite COBISS kodo dosežka – sistem nato sam izpolni naslov objave, naziv, IF in srednjo vrednost revije, naziv FOS področja ter podatek, ali je dosežek uvrščen v A'' ali A'. Nazaj

[6] Navedite družbeno-ekonomske dosežke, ki so nastali v okviru tega projekta. Družbeno-ekonomski rezultat iz obdobja izvajanja projekta (do oddaje zaključnega poročila) vpišete tako, da izpolnite COBISS kodo dosežka – sistem nato sam izpolni naslov objave, naziv, IF in srednjo vrednost revije, naziv FOS področja ter podatek, ali je dosežek uvrščen v A'' ali A'.

Družbeno-ekonomski dosežek je po svoji strukturi drugačen kot znanstveni dosežek. Povzetek znanstvenega dosežka je praviloma povzetek bibliografske enote (članka, knjige), v kateri je dosežek objavljen.

Povzetek družbeno-ekonomskega dosežka praviloma ni povzetek bibliografske enote, ki ta dosežek dokumentira, ker je dosežek sklop več rezultatov raziskovanja, ki je lahko dokumentiran v različnih bibliografskih enotah. COBISS ID zato ni enoznačen, izjemoma pa ga lahko tudi ni (npr. prehod mlajših sodelavcev v gospodarstvo na pomembnih raziskovalnih nalogah, ali ustanovitev podjetja kot rezultat projekta … - v obeh primerih ni COBISS ID). Nazaj

[7] Navedite rezultate raziskovalnega projekta iz obdobja izvajanja projekta (do oddaje zaključnega poročila) v primeru, da katerega od rezultatov ni mogoče navesti v točkah 6 in 7 (npr. ni voden v sistemu COBISS). Največ 2.000 znakov, vključno s presledki. Nazaj

[8] Pomen raziskovalnih rezultatov za razvoj znanosti in za razvoj Slovenije bo objavljen na spletni strani: http://sicris.izum.si/ za posamezen projekt, ki je predmet poročanja Nazaj

[9] Največ 4.000 znakov, vključno s presledki Nazaj

[10] Največ 4.000 znakov, vključno s presledki Nazaj

[11] Rubrike izpolnite / prepišite skladno z obrazcem "izjava sofinancerja" http://www.arrs.gov.si/sl/progproj/rproj/gradivo/, ki ga mora izpolniti sofinancer. Podpisan obrazec "Izjava sofinancerja" pridobi in hrani nosilna raziskovalna organizacija – izvajalka projekta. Nazaj

[12] Navedite en izjemni znanstveni dosežek in/ali en izjemni družbeno-ekonomski dosežek raziskovalnega projekta v letu 2013 (največ 1000 znakov, vključno s presledki). Za dosežek pripravite diapozitiv, ki vsebuje sliko ali drugo slikovno gradivo v zvezi z izjemnim dosežkom (velikost pisave najmanj 16, približno pol strani) in opis izjemnega dosežka (velikost pisave 12, približno pol strani). Diapozitiv/-a priložite kot priponko/-i k temu poročilu. Vzorec diapozitiva je objavljen na spletni strani ARRS http://www.arrs.gov.si/sl/gradivo/, predstavitve dosežkov za pretekla leta pa so objavljena na spletni strani http://www.arrs.gov.si/sl/analize/dosez/. Nazaj

Obrazec: ARRS-RPROJ-ZP/2014 v1.03
05-B7-B6-BB-2B-6D-11-C1-C6-6A-7B-6F-B7-18-0F-DB-80-5A-49-E9

Priloga 1

incoherent and would require both a slit and a collimating mirror. In principle, the signal-to-noise ratio obtainable would be similar to that of a grating instrument at the same resolution. Whether or not it will be possible to exploit the potentially higher resolution will depend on the luminance of the source, but the high wavenumber accuracy will nevertheless remain an important advantage.

We should expect many further results from this exciting new instrument, both in its present form at Synchrotron SOLEIL and in new applications elsewhere with different light sources. ❐

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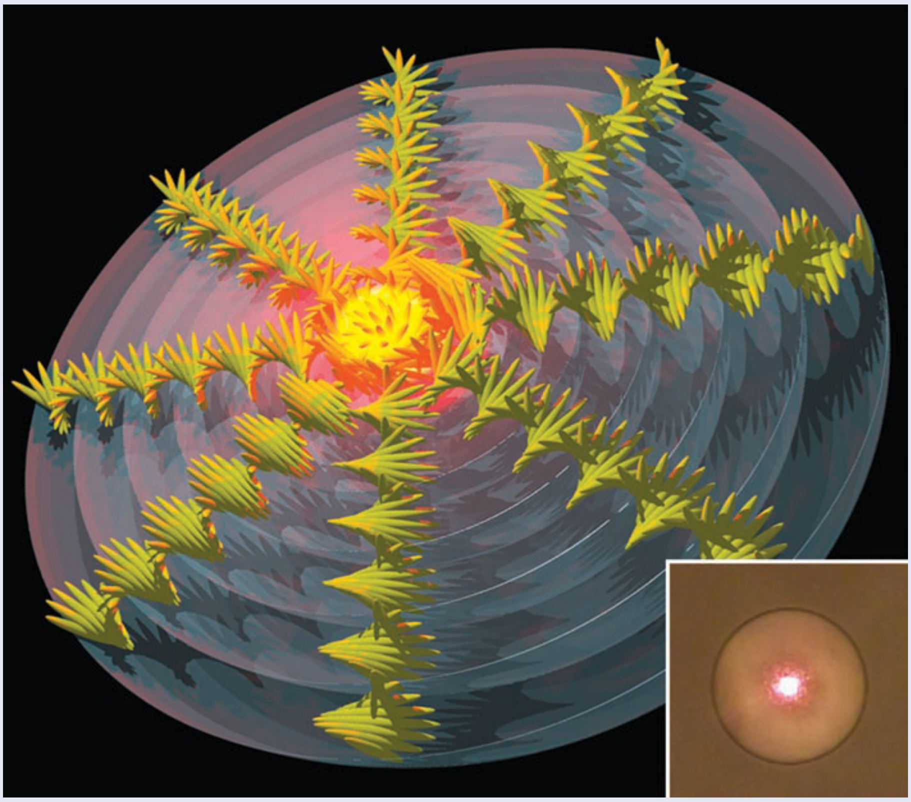
LIQUID CRYSTALS

Tiny tunable 3D lasers

Integrated photonics applications require lasers that are cheap, highly tunable, can emit light in all directions and have low thresholds, narrow linewidths and ultrasmall mode volumes. The recent findings of Matjaž Humar and Igor Muševič from the J. Stefan Institute and University of Ljubljana in Slovenia may fulfil these requirements (*Opt. Express* **18,** 26995–27003; 2010).

Instead of building a solid-state 3D microlaser, the researchers opted for a soft-matter approach. “Soft matter has an inherent natural ability to self-assemble into a variety of structures that are potentially interesting for photonic applications,” explained Muševič.



Humar and Muševič created their microlaser by placing a 15–50-μm-diameter microdroplet of cholesteric liquid crystals doped with a laser dye into an isotropic carrier fluid. Dispersing the microdroplet in an immiscible fluid such as glycerol allowed it to spontaneously self-assemble into an aspherical shape because of surface tension. Strong periodic modulation of the refractive index induced by the chirality of the cholesteric liquid crystals caused the formation of a multilayered spherical Bragg resonator. This microresonator can be thought of as hundreds of concentric shells of alternating refractive index.

Optically pumping the microdroplet with external pulses caused the photonic bandgap in the Bragg resonator to concentrate the light emitted from the dye molecules inside the microdroplet, thereby emitting monochromatic light in all directions. Specifically, lasing was observed at ~600 nm with a linewidth of ~0.1 nm at a threshold of ~1.8 mJ cm^{-2} when a 1 ns pumping pulse from a *Q*-switched frequency-doubled Nd:YAG laser was used to uniformly illuminate a 40-μm-diameter microdroplet. The average output power was reported to be 0.05 mW at a repetition rate of 200 Hz.

The dependence of the lasing wavelength on the helical period of the cholesteric liquid crystals allowed it to be tuned simply by varying the temperature of the system. The researchers demonstrated a reversible temperature tuning of ~35 nm at 3.5 nm K^{-1}. They also pointed out that the lasing threshold was dependent on the number of layers in the microdroplet, corresponding to the *Q*-factor of the microcavity and hence to the diameter of the microdroplet. The smallest lasing-allowable diameter in the work was 15 μm.

According to the researchers, millions of identical microlasers can be produced in a fraction of a second, simply by mixing two different immiscible fluids. This is almost impossible to produce in a solid-state device — a clear advantage of the soft-matter approach.

“I expect that the long-term impact of these cheap, disposable and easy-to-produce microlasers as coherent, omnidirectional light sources might be for soft-matter integrated photonic circuits. In the short term, they might be useful for imaging and sensing,” said Muševič.

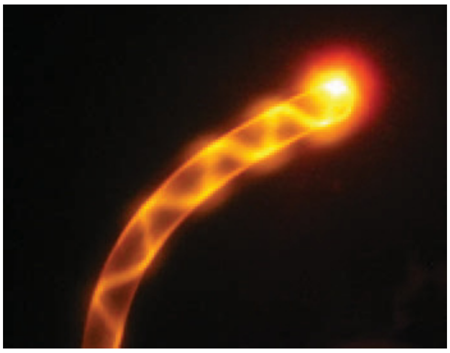
RACHEL WON

Priloga 2

LIQUID CRYSTALS

Self-assembled fibres

Opt. Express **21,** 30233–30242 (2013)



A new class of liquid-crystal-based optical fibres have been fabricated by scientists in Germany and Slovenia. They grew the fibres by self-assembly in an immiscible water-based mixture containing a surfactant. The fibres consist of a series of coaxial, rolled-up layers of the liquid crystal 8CB, and are highly birefringent. The size of the fibres varies with the exact growing conditions, but the researchers say that they typically have a diameter ranging from a few micrometres to about 100 μm, and can reach several centimetres in length. The fibres were observed to guide light, and, when doped with a suitable dye such as Nile Red and optically pumped, they can lase as a result of the creation of whispering gallery modes. The threshold for laser operation was estimated to be 75 μW cm^{-2} with emission occurring at around 630 nm. The team says that such soft-matter structures formed from complex ordered fluids represent an exciting new family of photonic devices that can be grown and manipulated in a manner similar to living organisms. *OG*

WHITE LEDS

Ultrathin emissive layers

Appl. Phys. Express **6,** 122101 (2013)

Hybrid white organic light-emitting diodes (WOLEDs) commonly employ two emissive layers of different colours — one doped with blue fluorescent emitters and the other with green or red/orange phosphorescent emitters — to generate white light. They are highly promising light sources for display and lighting applications. Now, scientists based in Guangzhou, China, have realized high-performance hybrid WOLEDs that use ultrathin emissive layers. They found that the efficiency of their devices increases significantly as the emissive layers are made thinner. For example, a device with a 0.2-nm-thick phosphorescent emissive layer exhibited a high power efficiency of 7.3 lm W^{-1} and a high luminance of 46,923 cd m^{-2}. In addition, its efficiency dropped very little as the current density was increased. A second hybrid WOLED in which both the blue and orange emissive layers were thinner than 1 nm had an even higher efficiency of 8.9 lm W^{-1} as well as a low driving voltage and a high colour-rendering index of 75. *SP*

DISPLAYS

Wide-angle head-up display

Appl. Opt. **53,** A121–A124 (2014)

Head-up displays are widely used in the aviation industry to display important information on the cockpit windows of aircraft, reducing the need for pilots to look down to read instruments. The same approach is also being considered for use in road vehicles to improve road safety. Most head-up displays reflect light into the user's eyes, but this method produces ghost images as the result of multiple reflections. Now, researchers in Taiwan have produced a design for a head-up display that instead uses scatter to display the image and offers a large viewing angle. The scatterers consist of a regular array of narrow Al_2O_3 columns that are fabricated by using a combination of atomic-layer deposition and electron-beam evaporation to deposit Al_2O_3 on a template of hollow nanospheres. Like conventional head-up displays, this display still requires drivers to adjust the focal distance of their eyes to read the information. *SP*

METAMATERIALS

Nanoantenna holography

Nature Commun. **4,** 2808 (2013)

Metasurfaces — engineered monolayers with custom-designed optical properties — offer a new medium for performing high-resolution holography, according to Lingling Huang and a team of researchers from the UK, China, Germany and Singapore. They report how metasurfaces composed of an array of subwavelength metallic nanoantennas are proving valuable for performing three-dimensional holography at visible and near-infrared wavelengths. The nanoantennas serve as pixels, and their orientation angle stores the phase information needed to recreate the hologram. Experiments were performed with an array of gold antennas that had dimensions of 150 × 75 nm^2. The information required to create a three-dimensional airplane model that was a few hundred micrometres in size was stored in the orientation of the antennas during fabrication of the metasurface hologram. The hologram consisted of 800 × 800 pixels, and had a lattice constant of 500 nm. The images were reconstructed at wavelengths of 670 nm, 810 nm and 950 nm. Importantly, the use of a metasurface eliminated the undesirable effect of multiple diffraction orders that usually accompany holography. *NH*

QUANTUM OPTICS

Nondestructive detection

Science **342,** 1349–1351 (2013)

Optical detectors usually annihilate a photon on detection, with the photon being absorbed by the detector material. However, Andreas Reiserer and co-workers from the Max-Planck-Institut für Quantenoptik in Germany have now demonstrated a novel non-destructive scheme for detecting photons. The photon detector consists of a Fabry–Pérot resonator containing a single trapped ^{87}Rb atom. The cavity induces strong coupling between a light pulse and the atom when it is one of two states, but not when the atom is in the other state. These atomic states are controlled by Raman lasers. When the atom is not coupled to the incoming light, the photon enters the cavity before being reflected. Although there is no atom–photon interaction, the photon induces a phase shift of π in the state of the atom. In contrast, when the atom is coupled, the photon is reflected without entering the cavity, and hence it does not induce a phase shift. By reading out the atomic phase, it is possible to detect a photon without it being absorbed. This detector achieved a single-photon detection efficiency of 74%. *NH*

OPTICAL SWITCHES

Photochromic gate

Appl. Phys. Lett. **103,** 221115 (2013)

Martti Pärs and colleagues from the University of Bayreuth in Germany have fabricated an optical gate for controlling the fluorescence emitted from a chromophore. This approach allows the emission of millions of photons to be modulated by the absorption of just tens of photons. It relies on creating a molecular triad that combines two fluorescent molecules of perylene

Priloga 3

Optics Express: World's First Microlaser Emitting in 3D			
Date	Title	Outlet	
9.12.2010	World's First Microlaser Emitting in 3D	1st Discount Brokerage	
9.12.2010	World's First Microlaser Emitting in 3D	6abc.com/WPVI	
9.12.2010	World's First Microlaser Emitting in 3D	740 KVOR	
9.12.2010	World's First Microlaser Emitting in 3D	7Online.com/WABC New York	
9.12.2010	World's First Microlaser Emitting in 3D	A.M. Best Company	
9.12.2010	World's First Microlaser Emitting in 3D	ABC11TV	
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9.12.2010	The Optical Society World's First Microlaser Emitting in 3D	ADVFN India	2.357
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9.12.2010	World's First Microlaser Emitting in 3D	Boston Globe	222.683
9.12.2010	World's First Microlaser Emitting in 3D	Boston Merchant Financial	
9.12.2010	World's First Microlaser Emitting in 3D	Boston Mutual Funds Exchange	
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8.12.2010	World's First Microlaser Emitting in 3D	DCCCafe	7.020
9.12.2010	World's First Microlaser Emitting in 3D	Dealbreaker	
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World's First Microlaser Emitting in 3D

Scientists in Slovenia Describe Practical, Tunable, 3D Microdroplet Laser in Optics Express

WASHINGTON, Dec. 8 — Versatile electronic gadgets should employ a number of important criteria: small in size, quick in operation, inexpensive to fabricate, and deliver high precision output. A new microlaser, developed at the Jožef Stefan Institute in Ljubljana, Slovenia embodies all these qualities. It is small, tunable, cheap, and is essentially the world's first practical three-dimensional laser.

As described in Optics Express, an open-access journal published by the Optical Society (OSA), Slovenian scientists Matjaž Humar and Igor Muševič have developed a microdroplet 3-D laser system in which laser light shines forth in all directions from dye molecules lodged within spherical drops of helical molecules dispersed in a liquid solution.

This is the first practical 3-D laser ever produced," says Muševič, who expects that the microdroplet lasers, which can be made by the millions in seconds, will be used in making arrays of coherent light emitters. These will be handy for a variety of imaging purposes, for example "internal-source holography." Here a 3-D laser would be embedded inside the object which is to be imaged; light coming directly from the source interferes with the light scattered by the surroundings. A three-dimensional image of the object can then be reconstructed from the interference pattern.

The helical molecules are cholesteric liquid crystals, related to the molecules that form the backbone of liquid crystal displays. The cholesteric molecules don't mix well with the surrounding polymer liquid. This incompatibility sets up a curious condition: the index of refraction of the cholesteric liquid crystal varies periodically outwards through the body of the 15-micron-sized droplet. It's as if the droplet were an onion with the layers corresponding to materials with a different index of refraction.

Most lasers possess two important ingredients: an active medium in which energy can be turned into light and amplified, and some resonant enclosure in which the developing coherent light can build up to a potent beam emerging as laser light. In the case of the microdroplet laser, the active medium consists of all those fluorescent dye molecules nestled in the liquid crystals. And the resonant enclosure consists not of the usual longitudinal shaped mirrored cavity, but of the nested sequence of "onion-layer" regions of changing index of refraction.

Two more features make this laser design highly workable. First, the laser components are self-assembled. Instead of an expensive fabrication process, the parts of the laser assemble spontaneously through chemistry. Second, the laser can be tuned: by changing the pitch size of the helical molecules --the degree of their corkscrew thread-- the wavelength of the light can be altered.

"Scientists have been trying to make these lasers from solid state materials, but you can imagine how difficult it is to make hundreds of alternating shells of optical materials, which should be very uniform," said Muševič. "The beauty of our approach is that such a 3-D onion droplet is self-assembled in a fraction of a second."

To tune the laser you don't even have to replace the droplets. Their optical properties can be changed by modifying the temperature. Tuning might even be accomplished by applying an extra electric field to the drops.

Last year, an early version of the 3-D laser resonator was reported. Now in the journal Optics Express, the fully tunable version of the laser is described.

The paper "3D microlasers from self-assembled cholesteric liquid-crystal microdroplets" by Matjaž Humar and Igor Muševič appears in the journal Optics Express. It can be accessed at: http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-18-26-26995

The authors' lab website is located at http://www.softmatter.si.

About Optics Express
Optics Express reports on new developments in all fields of optical science and technology every two weeks. The journal provides rapid publication of original, peer-reviewed papers. It is published by the Optical Society and edited by C. Martijn de Sterke of the University of Sydney. Optics Express is an open-access journal and is available at no cost to readers online at http://www.OpticsInfoBase.org/OE.

About OSA
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http://www.opticsinfobase.org/spotlight/summary.cfm?uri=oe-21-25-30233

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Lasing and waveguiding in smectic A liquid crystal fibers

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by Karthik Peddireddy, V. S. R. Jampani, Shashi Thutupalli, Stephar Herminghaus, Christian Bahr, and Igor Muševič

Source article Abstract | Full Text: XHTML | Full Text: PDF

Spotlight summary: As a materials scientist who plies his trade to optical fibers, I never ceas inspired by the breadth of materials-related opportunities for enabling next generation photonic work by Peddireddy *et al.*, which stems from a collaboration between Max Planck Institute for Self Organization (Goettingen, Germany), the Stefan Institute (Ljubljiana, Slovenia), and the F Mathematics and Physics (Ljubljiana, Slovenia), is an excellent case in point.

Entitled "Lasing and waveguiding in smectic A liquid crystal optical fibers", the work employs a process inherent to liquid crystals. As a brief primer, thermotropic liquid crystals are anisotropi molecules that spontaneously align depending on temperature. Nematic liquid crystals arise w organic molecules align ('nematic' derives from the Greek for 'thread'). Previous work by other that the (typically) spherical shapes of nematic phases when formed in immiscible fluids can e of microphotonic devices including resonators, lasers, and whispering gallery mode structures smectic-A liquid crystals are employed because their microstructure in this case is of coaxial o such that precisely sized fibers result. Additionally, the resultant fibers should possess a topolo defect aligned with the fiber's longitudinal axis which should reduce the likelihood of scattering