Anja Bregar
Kamnik pod Krimom 151
1352 Preserje

Fakulteta za matematiko in fiziko
Jadranska 9
1000 Ljubljana

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Prošnja za odobritev teme doktorske disertacije

Spoštovani,
podpisana Anja Bregar prosim za odobritev teme doktorske disertacije z naslovom "Flow of light in metamaterials based on nematic fluids" (Tok svetlobe v metamaterialih na osnovi nematskih tekočin). Prosim vas za odobritev pisanja disertacije v angleškem jeziku.

S spoštovanjem,

Anja Bregar

Priloge:

- življenjepis,
- osebna bibliografija,
- utemeljitev teme disertacije v slovenskem in angleškem jeziku z literaturo.

Življenjepis

Anja Bregar

30. marec 2017

Anja Bregar se je rodila 9. oktobra 1991 v Ljubljani. Osnovno šolo je obiskovala v Preserju pod Krimom in se nato leta 2006 vpisala v matematični oddelek Gimnazije Bežigrad. Kot nadarjena učenka je prejemala Zoisovo štipendijo, gimnazijo pa je zaključila kot diamantna maturantka. Leta 2010 se je vpisala na prvostopenjski študij fizike na Fakulteti za matematiko in fiziko Univerze v Ljubljani in ga zaključila leta 2013. V istem letu je nadaljevala z drugostopenjskim študijem fizike, smer Fizika kondenzirane snovi, ki ga je končala leta 2015. Zaposlila se je kot mlada raziskovalka v Skupini za fiziko mehke in delno urejene snovi na Fakulteti za matematiko in fiziko Univerze v Ljubljani pod mentorstvom doc. dr. Mihe Ravnika. Ukvarja se z numeričnimi simulacijami propagacije svetlobe skozi kompleksne nematske materiale ter z metamateriali. V letu 2016 se je udeležila treh poletnih šol in ene konference, kjer je imela predstavitev s plakatom. Habilitirana je kot asistentka, v šolskih letih 2015/16 in 2016/17 je vodila vaje iz Fizike za študente biologije.

Anja Bregar

Osebna bibliografija za obdobje 2015-2017

ČLANKI IN DRUGI SESTAVNI DELI

1.08 Objavljeni znanstveni prispevek na konferenci

1. OBLAK, Peter, GRADIŠEK, Miha, BREGAR, Anja, KRIŽAJ, Dejan. Sistem za generiranje ultrazvočnih pulzov za raziskave v medicini. V: ZAJC, Baldomir (ur.), TROST, Andrej (ur.). *Zbornik štiriindvajsete mednarodne Elektrotehniške in računalniške konference ERK 2015, 21. - 23. september 2015, Portorož, Slovenija*, (Zbornik ... Elektrotehniške in računalniške konference ERK ..., ISSN 1581-4572, 24). Ljubljana: IEEE Region 8, Slovenska sekcija IEEE, 2015, zv. A, str. 31-34, ilustr. [COBISS.SI-ID 11130708]

1.10 Objavljeni povzetek znanstvenega prispevka na konferenci (vabljeno predavanje)

2. RAVNIK, Miha, BREGAR, Anja, APLINC, Jure. Control of double refraction in anisotropic metamaterials. V: *SPIE Photonics West 2017, 28 January-2 February 2017, San Francisco, California, USA. OPTO : technical summaries* . [Bellingham]: SPIE, 2017, str. 394. `http://spie.org/Documents/ConferencesExhibitions/PW17O-Abstracts-lr.pdf` . [COBISS.SI-ID 3063908]

1.12 Objavljeni povzetek znanstvenega prispevka na konferenci

3. BREGAR, Anja, RAVNIK, Miha. Refraction on a flat interface of an optically anisotropic metamaterial. V: *6th Workshop on Liquid Crystals for Photonics, 14-16 September 2016, Ljubljana* . [Ljubljana: Institute Jožef Stefan, University of Ljubljana, Faculty of Mathematics and Physics, 2016], str. 44. [COBISS.SI-ID 3012708]

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2.09 Magistrsko delo

6. BREGAR, Anja. *Negativni lom na ravni površini optičnega metamateriala : magistrsko delo.* Ljubljana: [A. Bregar], 2015. 50 str., ilustr. [COBISS.SI-ID 2846052]

IZVEDENA DELA (DOGODKI)

3.15 Prispevek na konferenci brez natisa

7. BREGAR, Anja. *Refraction on a flat interface of an optically anisotropic metamaterial : poster presented at the summer school Active Complex Matter, Cargèse, Corsica Island, France, July 12- 23, 2016.* [COBISS.SI-ID 3071588]

SEKUNDARNO AVTORSTVO

Urednik

8. BREGAR, Anja (urednik), ČOPAR, Simon (urednik), KOS, Žiga (urednik), RAVNIK, Miha (urednik). *6th Workshop on Liquid Crystals for Photonics, WLCP 2016, Jožef Stefan Institute, Ljubljana, Slovenia, 14-16 September 2016.* Ljubljana: Institute Jožef Stefan: Faculty of mathematics and physics, 2016. `http://wlcp2016.fmf.uni-lj.si/wlcp-program-book.pdf` . [COBISS.SI-ID 3011428]

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Tok svetlobe v metamaterialih na osnovi nematskih tekočin

Avtorica: Anja Bregar Mentor: Miha Ravnik

31. marec 2017

Optični metamateriali so zanimivo področje fizike materialov, za katere so značilne izjemne optične lastnosti [1]. Osnovna lastnost metamaterialov je njihova umetno ustvarjena zgradba: zgrajeni so iz periodičnih enotskih celic, ki so v splošnem nekajkrat manjše od valovne dolžine svetlobe, ki jo želimo nadzorovati. Tako se svetloba širi skozi material, kot bi bil ta homogen. Ker pa lahko specifične geometrijske lastnosti in kemijsko sestavo periodičnih enot prilagajamo, je lahko tudi optični odziv takega kompozita do neke mere nadzorovan. Od poznih 90tih let se je polje metamaterialov razširilo na mnogo raziskovalnih področij. V začetnih letih je bilo veliko zanimanja predvsem za materiale, katerih lomni količnik bi bil za izbrane valovne dolžine negativen. Primeri materialov z negativnim lomnim količnikom so bili pokazani eksperimentalno za svetlobo od infrardeče do optičnih valovnih dolžin [2, 3]. Z njimi je bilo zasnovanih in ustvarjenih tudi nekaj privlačnih aplikacij, npr. leče z resolucijo pod uklonsko limito [4] in t.i. plašči nevidnosti [5]. A zaradi visokih izgub znotraj kovinskih delcev pri optičnih frekvencah in zaradi težav pri sestavljanju metamaterialov se je pobuda v zadnjem času preselila od razvoja tridimenzionalnih kovinskih metamaterialov k dielektričnim metamaterialom [6], katerih izgube so manjše, in metapovršinam – dvodimenzionalnim metamaterialom [7]. Z metapovršinami je mogoče natančno načrtovati fazo in polarizacijo prepuščene svetlobe [8] in jih uporabljati kot selektivne absorberje. Zasnovani so bili tudi metamateriali s poudarjeno optično anizotropijo – hiperbolični metamateriali [9], katerih dielektrični tenzor ima eno od lastnih vrednosti negativno. Z njimi je mogoče doseči negativni lom Poyntingovega vektorja, ne da bi bilo potrebno vplivati na vrednost magnetne permeabilnosti.

Naslednja velika skupina optičnih materialov so tekoči kristali, ki jih danes uporabljamo v različnih optičnih in fotonskih aplikacijah, posebej v tekočekristalnih zaslonih. So mehki materiali, sestavljeni iz paličastih molekul, ki so v določenem območju temperatur in molekulskih koncentracij orientacijsko urejene, a pozicijsko neurejene [10]. Iz njihovega orientacijskega reda izvirajo številne njihove lastnosti. Ena od njih je njihova anizotropna elastičnost: če z zunanjimi polji ali robnimi pogoji zmotimo orientacijski red, se prosta energija tekočih kristalov zviša. Strukturne in prostorsko odvisne sile, ki sledijo iz elastične proste energije, ustvarjajo množico različnih struktur in pojavov urejanja znotraj direktorskega polja. Nadalje iz orientacijskega reda sledi tudi optična anizotropija [11]: večinoma je izredni lomni količnik (vzdolž dolge osi molekul tekočega kristala) večji od rednega. Optična dvolomnost tekočih kristalov je uporabno orodje za nadzor toka svetlobe v optičnih sistemih. Ker je na tekoče kristale relativno lahko vplivati z zunanjimi polji, še posebej električnim poljem, ki obrne dolgo os tekočekristalnih molekul vzdolž polarizacije električnega polja, je možno nadzirati elastične in optične lastnosti tekočih kristalov. Dandanes se tekoče kristale raziskuje v različnih smereh, kot so npr. usmerjeno urejanje koloidnih kristalov [12, 13], zapletena topološka stanja [14, 15, 16] in mikrofluidika [17]. V širšem kontekstu fotonike aplikacije segajo na področja npr. senzorike [18], nastavljivih leč [19, 20], nastavljivih valovodov [21], in nastavljivih laserjev [22].

Področji tekočih kristalov in metamaterialov sta prepleteni s številnimi eksperimentalnimi in teoretičnimi primeri. Vredno je omeniti, da negativni lom ni omejen na področje metamaterialov: tekoči kristali in drugi dvolomni materiali lahko lomijo svetlobo negativno, ko svetloba na vzorec vpada skoraj pravokotno [23]. Holesterične tekočekristalne tanke plasti je mogoče uporabiti kot metapovršine zaradi njihove zmožnosti učinkovitega nadzora nad fazo prepuščene svetlobe [24]. S tekočimi kristali je bila dosežena orientacijska in do neke mere celo pozicijska urejenost sestavnih gradnikov metamateriala: izvedeni so bili eksperimenti z zlatimi nanopaličicami, ki so se zaradi svoje podolgovate oblike in elastičnosti tekočega kristala uredile [25, 26, 27]. Numerično pridobljeni lastni vrednosti tenzorja dielektričnosti materiala, sestavljenega iz kovinskih kroglic, razpršenih v tekočem kristalu, sta bili predznačeni nasprotno [28, 29]. Eksperimentalna dela kažejo, da imajo prevlečene zlate nanosfere, razpršene v nematskem tekočem kristalu, negativno redno in pozitivno izredno lastno vrednost tenzorja dielektričnosti pri nizkih frekvencah [30]. Druga možnost uporabe tekočih kristalov znotraj metamaterialov je nastavljanje lastnosti metamateriala z električnim poljem. Ko tekočekristalni metamaterial priključimo na napetost, lahko uravnavamo frekvenco, pri kateri imamo željene metamaterialne lastnosti [31, 32, 33], tekoče kristale pa je mogoče uporabiti tudi za vklapljanje in izklapljanje metapovršin [34].

Osnovna motivacija te disertacije je preučevati vlogo optične anizotropije pri širjenju svetlobe skozi metamaterial. Anizotropija je lahko v tem kontekstu značilnost metamateriala kot celote ali pa lastnost nekaterih njegovih sestavnih delov. S preučevanjem odziva na optično anizotropije se približujemo drugemu relevantnemu še odprtemu izzivu: ustvariti mehke metamateriale, katerih lastnosti bi bilo mogoče nastavljati z zunanjimi polji in parametri. Tovrstne anizotropne strukture, ki bi jih bilo mogoče nadzorovati, lahko dosežemo s kompleksnimi nematskimi tekočinami, morda v povezavi s koloidnimi vključki. Tako je končni cilj te disertacije raziskati možnosti za implementacijo nastavljivih mehkih metamaterialov.

Natančneje, ukvarjali se bomo z optično anizotropnimi sistemi, katerih lastni vrednosti tenzorja dielektričnosti sta predznačeni različno: z metamateriali, analognimi tekočim kristalom. Zanimal nas bo lom iz vakuuma v metamaterialni sistem z optično osjo, ki je homogena, a nagnjena glede na mejo med snovema. Kot nadgradnjo tega sistema bomo preučevali primer periodične modulacije direktorskega profila. Že obstoječe holesterične sisteme s pozitivnim lomnim količnikom, pri katerih se optična os zvija v ravnini, vzporedni z mejo med vakuumom in holesteričnim tekočim kristalom, bomo primerjali s holesteričnimi hiperboličnimi metamaterialnimi sistemi z eno ali dvema negativnima lastnima vrednostma dielektričnega tenzorja. Še posebej nas bo zanimal režim Braggovega odboja za krožno polarizirano svetlobo. Simulirali bomo tudi širjenje svetlobe pod kotom glede na spreminjajočo se optično os, za kar še ni jasnega teoretičnega modela. V splošnem bomo modulirali prostorsko spremenljiv in frekvenčno disperzen dielektrični tenzor in raziskali možnosti za učinkovito upravljanje s propagacijo svetlobe.

Nadzor nad tokom svetlobe bomo v kontekstu aplikacij kot so valovni vodniki in leče raziskovali tudi pri materialih s pozitivnim lomnim količnikom. Zanimiva priložnost za uporabo v valovnih vodnikih je ojačanje njihovih lastnosti s tekočimi kristali. V sodelovanju s prof. Etiennom Brasseletom z Univerze v Bordeauxu bomo simulirali in teoretično analizirali različne predloge za valovne vodnike, napolnjene s tekočimi kristali. Z različnimi robnimi pogoji in drugimi tehnikami je mogoče v tekočekristalnih valovnih vodnikih vzpostaviti različne direktorske profile. Prostorsko spreminjanje lomnega količnika lahko nato vpliva na propagacijo svetlobe. Z določenimi direktorskimi profili lahko dosežemo fokusiranje izbranih vpadnih polarizacij svetlobe. Posebej se bomo posvetili direktorskim profilom, ki svetlobo fokusirajo z pozitivno anizotropnimi tekočimi kristali ($n_o \leq n_e$), zaradi česar so strukture eksperimentalno lažje dosegljive.

S širšim ciljem ustvariti tridimenzionalni metamaterial iz samourejajočih se osnovnih gradnikov bi si radi ogledali urejanje kovinskih koloidnih delcev v tekočem kristalu. Ker so nekatere orientacije koloidnih delcev zaradi nematske proste energije tekočega kristala energijsko bolj ugodne [13, 35], je mogoče, da se koloidni delci podkvaste oblike samouredijo v dvo- in trodimenzionalne fotonske kristale. Razmerje med vplivom geometrijskih lastnosti takšnega koloidnega metamateriala in vplivom optičnih parametrov snovi, iz katerih so koloidi, tvori bogat in kompleksen raziskovalni sistem. Ker so optični parametri kovin močno odvisni od frekvence uporabljene svetlobe, dosegamo z različnimi valovnimi dolžninami kontrasten metamaterialni odziv. Eksperimentalna uresničitev teh idej bi potekala v mogočem sodelovanju s skupino prof. Muševiča na IJS-ju.

Širjenje svetlobe skozi metamateriale je zaradi različnih snovnih in geometrijskih lastnosti metamaterialnih gradnikov zelo zapletena. Tudi v tekočih kristalih je lahko zaradi zapletenih direktorskih struktur točen izračun toka svetlobe težaven. V tej luči so numerične simulacije ključno orodje za prepoznavanje odziva metamaterialnih nematskih struktur. Simulacije za to disertacijo bomo izvedli s programsko kodo, ki temelji na metodi FDTD in je implementirana znotraj skupine. Pri metodi FDTD (krajše za angl. finite-difference time-domain) [36], integriramo Maxwellove enačbe eksplicitno, zaradi česar je mogoče različne optične pojave obravnavati enostavneje. Diferencialne enačbe integriramo na Yeejevi mreži, v kateri so komponente električnega in magnetnega polja postavljene v kubični zamaknjeni rešetki in časovno propagirane z medsebojnim časovnim zamikom. Naša koda je prilagojena za optično anizotropne materiale in tudi za anizotropne in frekvenčno disperzne materiale s prilagojeno metodo ADE (angl. auxiliary differential equation [36]). Frekvenčno disperzno funkcijo snovi lahko opišemo s plazemskim, Drudejevim ali Lorentzovim modelom.

Medtem ko je glavni cilj te disertacije raziskati optični odziv mehkih metamaterialov, je nujno upoštevati tudi relaksacijo tekočih kristalov zaradi optičnih električnih polj. To bo opravljeno z algoritmi za minimizacijo proste energije [37], ki so prav tako implementirani znotraj naše skupine. Programska koda upošteva različne časovne skale za širjenje svetlobe ($\approx$ ps) in relaksacijo tekočega kristala ($\approx$ ms).

Če povzamemo, v tej disertaciji bomo opisali konceptualno različne kombinacije optičnih metamaterialov in tekočih kristalov, katerih skupna točka bo optična anizotropija. Po eni strani se bomo ukvarjali s homogeniziranimi materiali z izrednimi lastnostmi, po drugi strani pa z načrtovanjem mehkih koloidnih metamaterialov. S tem delom bi radi predlagali nov pogled na nadzor in manipulacijo svetlobe.

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Flow of light in metamaterials based on nematic fluids

Author: Anja Bregar   Advisor: Miha Ravnik

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Optical metamaterials are a fascinating segment of materials science and are characterised by their extraordinary optical properties [1]. The defining feature of metamaterials is their man-made composition: they are built in periodic unit cells with periodicity generally several times smaller than the wavelength of operating light waves, with the intent of light propagating through the material as if the material was homogeneous. However, since the specific geometric characteristics and the material composition of the periodic building blocks can be adjusted, the optical response of such a composite can be, to an extent, engineered. Since the early 2000s, the field of metamaterials' research has expanded to many different areas of investigation. The central interest at the beginning was to obtain materials which could produce negative refractive index for light in some chosen range of wavelengths, which has been experimentally observed for wavelengths from infrared to optical [2, 3]. With negative-index materials, some attractive applications have been constructed, for instance lenses with subwavelength resolution or invisibility cloaks [4, 5]. But because of the high losses inside metals at optical frequencies and fabrication difficulties, the incentive has lately moved from producing bulk metamaterials with metallic components towards other options, like metamaterials made from dielectrics [6], which have lower losses, and metasurfaces – 2D metamaterials [7]. With metasurfaces, it is possible to precisely shape the wavefront – design the phase and polarisation – of the transmitted light [8], and use them as selective absorbers. While it is difficult to construct optically perfectly isotropic metamaterials, the anisotropy has also been exploited in the field of hyperbolic metamaterials [9], which have an anisotropic permittivity tensor with some eigenvalues negative. With it, negative refraction of the Poynting vector can also be achieved without the need for negative permeability.

Liquid crystals are another major family of optical materials, today used widely in various optic and photonic applications, especially displayes. They are soft materials made from rod-like molecules, which in a range of temperatures and molecular concentrations posess a degree of orientational order in contrast to their positional disorder [10]. Their orientational order is the origin of several other characteristics. One of them is their anisotropic elasticity: the free energy of liquid crystals increases, if – because of external fields or boundary conditions – their orientational order is disturbed. The structural and spatially dependent forces, which arise from that account, generate a plethora of field structures and ordering phenomena. Furthermore, their orientational order implies optical anisotropy [11]: mostly, liquid crystals possess an extraordinary index of refraction (along the long axis of the molecules) larger than the ordinary index. Their optical birefringence is an noteworthy tool in the control of flow-of-light in optical systems. Since liquid crystals are also relatively easily manipulated with external fields, especially electric field, which tends to turn the long axis of the liquid crystal molecules to be polarized along the field, the elastic and optical properties can be well controlled. Today, liquid crystals are explored in various directions, such as the controlled assembly of colloidal crystals [12, 13], research of complex topological states [14, 15, 16] and microfluidics [17]. In the broader context of photonics, diverse applications lie in the fields of sensing [18], tunable lenses [19, 20], tunable waveguides [21], and tunable lasers [22].

The fields of liquid crystals and metamaterials are intertwined in a number of experimental and theoretical examples. It is worth mentioning negative refraction is not limited to metamaterials: liquid crystals and other birefringent materials can refract light negatively, when the incoming angle of light is almost perpendicular [23]. Cholesteric liquid crystal films have been used as metasurfaces because of their capability to efficiently control the phase of the transmitted light [24]. Liquid crystals have been used to achieve orientational or even to an extent positional ordering of metamaterial constituent parts: numerous experiments have been performed with golden nanorods ordering because of their prolong shape in connection with the elasticity of liquid crystals [25, 26, 27]. Numerical analysis has suggested that a material composed of metallic spheres, dispersed in liquid crystal, would have the eigenvalues of permittivity tensor signed oppositely [28, 29]. Experiments have been performed in that direction which show that coated gold nanospheres dispersed in nematic liquid crystals have a negative ordinary and positive extraordinary eigenvalues of the permittivity tensor at low frequencies [30]. Another usage of liquid crystals inside metamaterials was to adjust the metamaterial properties with electric field. With applying voltage, the operational frequency of the metamaterial can be fine-tuned [31, 32, 33], and the liquid crystals can be used to switch between the on- and off-states of a metasurface [34].

The primary motivation behind this thesis is to study the role of optical anisotropy on the propagation of the light fields through the metamaterial. The anisotropy could be a feature of the metamaterial as a whole or a characteristic of some of its constituent parts. By studying the anisotropy, we are moving towards another very relevant open challenge: to create a controllable soft metamaterial, whose properties could be tuned with external fields and parameters. Complex nematic fluids, perhaps combined with colloidal inclusions, can achieve such anisotropic controllable structures. So the end goal of this thesis is to explore the possibilities for the implementation of tunable soft metamaterials.

Specifically we will address optically anisotropic systems with the eigenvalues of the permittivity tensor with different signs: liquid-crystal like metamaterials. We will be interested in a case of refraction from vacuum into a system with optical axis homogeneous across the material and tilted with respect to the metamaterial boundary. As an upgrade of these systems, examples with periodic modulation of the director profile will be examined. As a comparison with the already existing cholesteric positive-refractive-index systems, where the optical axis is twisting in the plane parallel to the material boundary, we will explore cholesteric hyperbolic metamaterial systems with some of the permittivity eigenvalues negative. We will be especially interested in the Bragg-reflective regime for circularly polarised light. Additionally, we will perform simulations of the propagation of light at an angle with the optical axis, for which no clear theoretical framework has yet been established. In general, we will model spatial modulation of frequency-dispersive permittivity tensor and explore possibilities for successful manouvering of light propagation.

The control over the flow of light will be explored for materials with all-positive refractive index as well in the context of metamaterial applications, such as waveguides and lenses. An appealing option for waveguiding is to enhance the properties of waveguides with liquid crystals. In cooperation with prof. Etienne Brasselet from University of Bordeaux, different proposals for waveguides, filled with liquid crystals, will be simulated and analysed theoretically. Through different boundary conditions and other manipulation, different director profiles can be introduced into the liquid crystal waveguide. The modulation of the refractive index profile can in turn affect the propagation of light. With some director profiles we can achieve focusing of selected incoming polarizations. Special emphasis will be put on the director profiles which exhibit focusing for positive anisotropy ($n_o < n_e$), so the structures are easily obtainable experimentally.

To auto-compose a bulk metamaterial from bottom scales up, we would like to assess self-assembly of metallic colloidal particles in liquid crystals. As some orientations of the colloidal particles are energetically more favourable because of nematic elastic energy [13, 35], the horseshoe-shaped colloids might self-assemble in 2D and 3D photonic crystals. The analysis of the interplay between the influences of the geometry of such a colloidal metamaterial and the optical parameters of the materials used for the colloids provides a rich case of study. Comparison of metallic colloidal inclusions with dielectric ones also gives experimental diversity. Since the optical parameters are highly dependent on the frequency of light, contrasting optical response is achieved across different wavelengths. Experimental realisation of these ideas would be explored in possible collaboration with the group of prof. Muševič at JSI.

Propagation of light through metamaterials is very complex due to various material characteristics and elaborate geometries of its constituent parts. In liquid crystals, the exact calculation of the flow of light can be, because of the complicated director field structures, equally challenging. With that in mind, numerical simulations are a viable tool in determining the response of such soft matter structures. The calculations for my thesis will be performed with computer code based on the FDTD method, which was implemented in our group. In FDTD (short for finite-difference time-domain) [36], Maxwell's equations are integrated quite explicitly, which allows for straightforward implementation of different optical phenomena. The differential equations are integrated over Yee mesh, in which the components of electrical and magnetic fields are positioned in a cubic stacked grid and propagated in a leapfrog fashion in time. Our code is adapted for optically anisotropic materials, as well as for anisotropic and frequency dispersive materials with the adapted ADE (auxiliary differential equation [36]) method. As a model for frequency dispersive dielectric function of a material, the plasma, Drude, and Lorentz models can be used.

While the main objective of this PhD is to explore the optical response of soft matter metamaterials, it is essential to take into account the relaxation of the liquid crystal because of the optical electric fields as well. This will be done with free energy minimisation algorithms, namely the relaxation algorithm [37], also incorporated in our group. The code takes into account different time scales of the light propagation ($\approx$ ps) and relaxation ($\approx$ ms).

To summarize, in the thesis we will consider conceptually different combinations of optical metamaterials and liquid crystals, linked together by the notion of optical anisotropy. On one hand we will deal with homogenised materials with exceptional properties, on the other hand we will aim to design a soft colloidal metamaterial from bottoms-up. With the work, we would like to propose a new perspective for the control and manipulation with light.

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