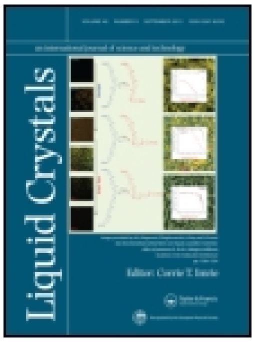

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INVITED ARTICLE

Integrated and topological liquid crystal photonics

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This contribution is a personal view of the rapidly developing subfield of nematic colloids, with an emphasis on possible applications of these materials in future photonic microdevices. A brief overview of the most important phenomena, observed in the past decade in nematic colloids is given. It is explained why integrated photonics based on microstructured liquid crystals is feasible and future challenges towards the realisation of integrated liquid crystal microphotonics are discussed.

Keywords: liquid crystals; photonics; liquid crystal colloids

Introduction

In their article entitled 'Photonic Band Structure: the Face-Centered-Cubic Case' published in *Physical Review Letters* in 1989 [1], Yablonovitch and Gmitter have introduced the term 'photonic bangap material' in obvious correspondence to the bandgap structure of the electronic levels in solids. Previously, Eli Yablonovitch [2] and Sajeev John [3] realised that the concepts of the Brilloiun zone and the band structure of energy levels should be applied to the spectrum of photons in 3D optically periodic structures, similar to the electron levels in solid crystals. They investigated the inhibition of spontaneous emission of electromagnetic radiation by atoms in an environment that controls their radiation field. At that time, the concept of the photonic band gap was actually already known and was used in many technical applications including Fabry–Perot microcavities for solid state lasers and intereference filters. This concept was also well known from the optics of cholesteric and ferroelectric liquid crystals (LCs). However, as it often turns out, this idea of the new field called 'photonics' soon gained huge attention because of its potential application in an entirely new generation of integrated photonic devices, which would be used to generate and control the flow of photons on a microscale. These hypothetical devices are therefore using the concept of the forbidden energy gap for photons to guide and control the flow of light, similar to the control of flow of electrons in integrated microchips. The idea of how to control the flow of light by a photonic crystal is very simple. The photonic crystal is characterised by a forbidden frequency gap in the dispersion relation linking the wave-vector and the frequency of the electromagnetic field, as illustrated in Figure 1. This means that electromagnetic radiation of frequency ω, which falls into this forbidden region, cannot propagate in the photonic crystal. As a result, such radiation will be reflected and the photonic crystal will act as a perfect lossless mirror. If the forbidden gap is complete, the light will be reflected for all angles of incidence. To make an integrated photonic device, one should be able to design and assemble photonic-like structures and interconnect them to the optical waveguides, optical sources, modulators and detectors. In such a hypothetical photonic microcircuit, the photons would play the role of the electrons in microelectronic circuits; they would carry the information at the speed of light with negligible delays

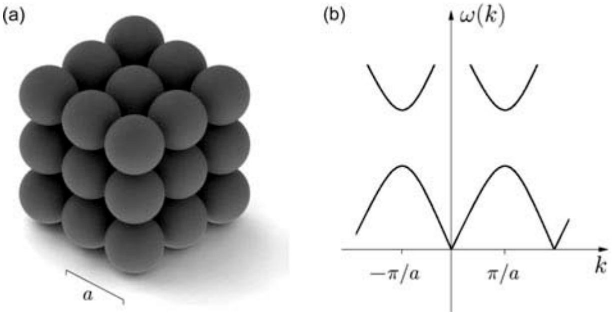

Figure 1. (a) Photonic crystal is a regular 3D arrangement of dielectric objects that are separated by a distance, comparable to the wavelength of light that is of our interest. (b) The dispersion relation for light, propagating in a photonic crystal is periodic in the reciprocal space. In the Brillouin zone, the frequency (energy) spectrum exhibits forbidden band(s), which are the result of Bragg interference of EM waves in periodic medium (image courtesy of E. Zupanič).

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and presumably at much lower power dissipation than superfast microelectronics of today [4].

These ideas soon gathered great scientific interest and the methods of assembly or preferably self-assembly of photonic crystals were for a decade one of the mainstream directions in the material science and photonic engineering. Methods of fabrication that were investigated include colloidal assembly of photonic crystals from water dispersions [5], directed assembly on patterned surfaces [6], electron-beam microlithography [7], optoelectronic tweezing [8], DNA-assisted colloidal assembly [9] and two-photon polymerisation [10]. Today, we are witnessing realisation of these ideas in numerous industrial photonic roadmaps and it is expected that hybrid photonic-electronic microcircuits will soon boost the performance of our computers by order(s) of magnitude. This will, without doubt, soon be realised in silicon platforms [11] that will merge the photonic large scale integration technologies with electronic large scale integration, and the main advantage will be very fast on-chip distribution of information via photonic highways and photonic floors embedded in standard silicon integrated circuitry.

While hybridisation of solid state photonics and microelectronics will, without doubt, make significant step forward on a shorter time scale, one can see the limitations of such an approach on a longer time scale. Solid matter is inherently immobile, and it is impossible to imagine any self-assembly mechanism involving only hard matter. It is also difficult to process solid matter on a nanometre scale to create smooth interfaces, along which the light could propagate without substantial losses. Solid matter also cannot heal and it seems difficult to grow complex shapes and architectures using the solid state. All these properties are, in fact, attributes of the liquids and soft matter, as evidenced by the examples in Nature that has created fascinating photonic structures, which can grow, self-assemble and (to a certain extent) heal. While soft matter, including LCs, is a poor electrical conductor, it is an excellent optical material with a highest known electro-optical response, the highest birefringence and optical nonlinearities, for example. By using soft matter and LCs it was possible to produce fascinating flat panel devices, which were not imaginable only twenty years ago.

The question is whether we could use LCs and soft matter in general, to design and produce soft matter photonic integrated devices of the future? To this aim, one has to prove that it is possible to produce coherent light on a microscale, as well as to guide it in a controllable way, process and detect it. Moreover, one should be able to assemble all these photonic elements in a kind of a microcircuit that is made of liquid matter, but is at the same time firmly bound into permanently functioning devices. Forces between objects in liquids are therefore needed in first place, and these forces should be strong enough to provide permanent binding of fluid microelements in 3D.

2D and 3D photonic crystals made of LC colloids

One of the first observations of forces between the objects in LCs was reported by Cladis, Pieranski and Rault [12,13] and were used to 'decorate' and visualise the orientation of the liquid crystalline molecules at the free surface of a nematic liquid crystal (NLC). Later on, the experiment of Poulin et al. [14] demonstrated striking fact that water droplets, immiscible with the NLC, could spontaneously arrange in chain-like structures, floating on the interface of the NLC. Each droplet was separated from its neighbour by a topological defect that provided stability against coalescence of water. There are two important messages from this work: (i) NLC can provide structural forces between included objects that are very strong, in fact, much stronger than $k_B T$, and (ii) the topology and topological defects are important for colloidal forces in the NLCs.

These two messages were the basis for rapid advancement in the field of nematic colloids after the year 2000, when the laser tweezers was introduced as a new and powerful tool for controlled manipulation of microparticles in LCs [15–20]. It was demonstrated that by using the laser tweezers, practically any kind of micrometre-sized particles could be trapped and manipulated by light. Using this tool, we were able to measure the forces and interactions between a pair of colloidal microparticles in colloidal dispersions and to elucidate the role of different topological defects of dipolar and quadrupolar symmetry (see, for example, [21,22]). We could also successfully assemble colloidal crystals by using the structural forces provided by elastically deformed NLC. Various 2D nematic colloidal crystals with different surface motifs were demonstrated [23–25], and recently a 3D nematic colloidal crystal was successfully assembled [26], as illustrated in Figure 2. In all these cases, the binding forces are provided by topological defects, i.e. the singularities of the order parameter field. These forces are of long range with the power-law decay of the pair interaction forces, giving rise to the pair interaction energies of up to several thousands of $k_B T$ per micrometre particle. They are still strong enough to bind a pair of 20 nm silica nanoparticles, as demonstrated recently in [27]. This means that building photonic crystals for the optical or IR wavelengths, which requires the photonic crystal lattice spacing of the order of 500 nm and several 100 nm diameter particles, is

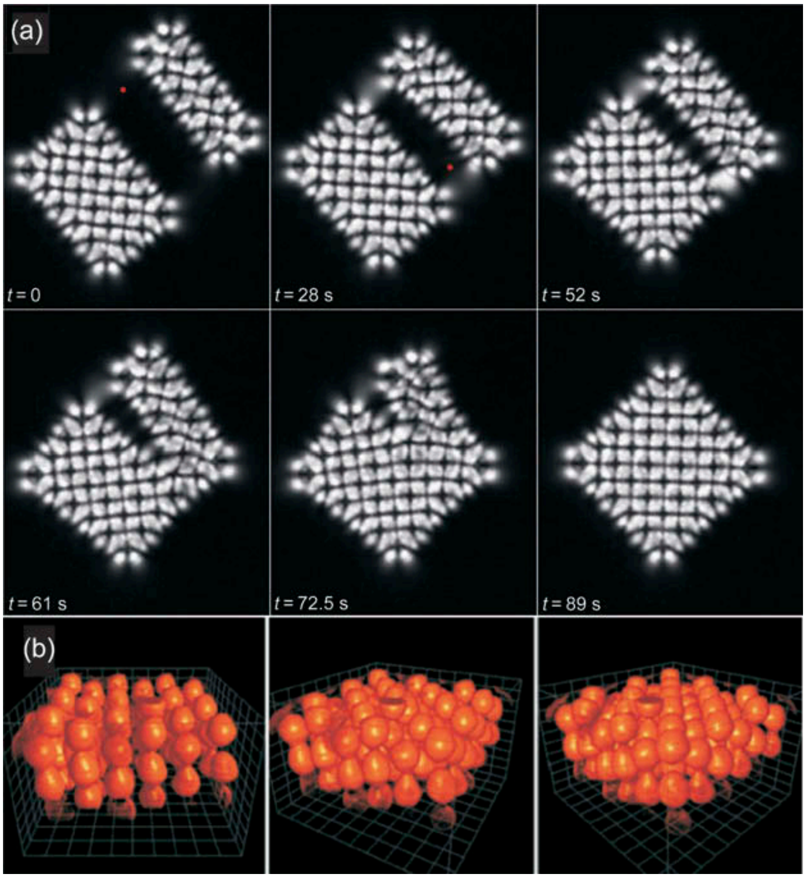

Figure 2. (Colour online) (a) Laser-tweezers assembly of a 3D dipolar colloidal crystal observed under crossed polarisers. Colloidal blocks of 2 × 6 × 3 and 4 × 6 × 3 particles assemble into the final 6 × 6 × 3 dipolar colloidal crystal. The assembly at the initial stage was guided by the laser tweezers until blocks started to attract themselves. In all images, the small red dot is the optical trap, used to direct the colloidal assembly. (b) 3D representation of the Fluorescence Confocal Polarised Microscopy image of a 6 × 6 × 3 3D dipolar colloidal crystal, revealing tetragonal symmetry of the unit cell (image courtesy of A. Nych and U. Ognysta).

quite realistic and technologically feasible. It is also interesting that nematic colloidal crystals, where the topological defects are responsible for binding forces, exhibit unusual material properties, such as giant electrostriction and electro-rotation, demonstrated in [26].

Colloidal entanglement, knotting and linking of defect loops

It came as a surprise when the laser tweezers was used to quench a small area of the NLC containing silica particles from the isotropic phase and to observe the formation of entangled colloidal structures, see [28]. Till then, topological defects in a form of singular points and loops (Saturn ring, [29]), surrounding each colloidal particle separately were known and it was beyond imagination that a single defect loop could extend over several colloidal particles, forming a tightly bound-entangled colloidal assembly. However, numerical simulations based on the Landau-de Gennes theory clearly predicted that such entangled states should exist, as shown in [30–32]. It was found in numerous experiments, performed in planar nematic cells, where the colloids are confined into a single colloidal layer forming a 2D system, that only 1D entangled colloidal structures are stable, in spite of theoretical predictions that 2D entangled structures should be stable as well. Three topologically different entangled structures were identified, all of them appearing in a form of colloidal wires, but no 2D stable colloidal entanglement were ever observed experimentally (see Figure 3).

The entanglement of colloidal particles by the topological defect loops is a fundamentally different phenomenon from the interactions of dipolar or quadrupolar interactions. While in the nematic colloidal interactions involving either point or Saturn ring defects, sharing of regions of the elastic distortion is a primary reason for the forces between particles, sharing of the same topological defect loop

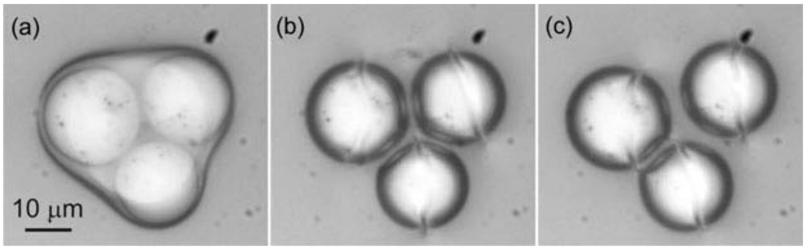

Figure 3. Colloidal entanglement in nematic liquid crystals. (a) Using high intensity laser tweezers, the nematic LC is molten into the isotropic phase, surrounding three colloidal particles. (b, c) After the light is shut-down, the isotropic phase is quenched into the nematic phase and only two colloidal particles are entangled, whereas the third particle shows isolated Saturn ring (upper-right in (c)) (image courtesy of M. Škarabot).

gives rise to the force between entangled colloids. The entanglement provides a strong, string-like force between colloidal particles, and the interaction is nearly an order of magnitude stronger than the dipolar colloidal interaction.

Colloidal entanglement is a topologically interesting phenomenon, because it addresses, for the first time, the questions of the distribution of the topological charge in such a topology, where the defect loops extend over several colloidal particles. Moreover, it addresses the question of the internal structure of –1/2 defect loops, which are involved in this case. Similar fundamental questions of the role of the topology in LC colloids were also raised in chiral nematic colloids, where much richer topological phenomena were observed. Tkalec et al. [33] found that in chiral LC environment closed defect loops can be entangled in such a way that they form knots and links, spanned on the scaffold of colloidal particles. Knots and links were formed around an array of colloidal particles in a chiral NLC, where each of the particles contributed its own Saturn ring. In the experiments, these defect rings were manipulated by the sharply focused beam of the laser tweezers. Using the deformation of the LC by the strong light of the tweezers, the individual rings were fused into larger defect rings, which could be further re-wired with themselves forming knots, or re-wired with neighbouring rings, forming links and more complex topological entities. It has been demonstrated that practically any kind of a knot or link could be created by taking a sufficiently large colloidal array. Knots and links in chiral nematic colloids are too of very few examples of the realisation of these abstract objects in real world, and were originally reported in chiral NLCs by Bouligand in 1974, see [34]. Recently, knots and links have been observed also in highly chiral nematic colloids [35], with the helical pitch comparable to the colloidal diameter. Other examples of knotted and linked fields include recently discovered knotted light field [36] and knotted vortices in fluids [37].

Do we need photonic crystals or we could self-assemble them from LCs?

We have demonstrated in 2009 [38] a conceptually new approach to the assembly of photonic microdevices by dispersing a thermotropic LC in an immiscible fluid, such as water. The result of immiscibility is the formation of spherical droplets of a NLC with well-defined internal director structure that could function as individual photonic elements of a micrometre size. In that case, we have shown that a NLC droplet with a radial director structure is an optical microcavity. An optical microcavity (or a microresonator) is an optical element that confines light to a very small volume. The confinement is realised either by the phenomenon of the total internal reflection (TIR) of light or by using the photonic crystal with its forbidden frequency gap. In the case of the nematic droplet dispersed in water, the higher refractive indices of the NLC result in the TIR of light that is created inside the resonator, see Figure 4. In the geometrical picture, light is circulating inside the droplet by subsequent reflections at the NLC–water interface. If it reaches the point of origin after one circulation with the same phase, we have the condition for an optical resonance. These resonant optical eigenwaves are called the Whispering Gallery Modes (WGMs) in accordance with the spectacular acoustical resonant phenomena in half-spherical domes. Mathematically, these waves are the solutions of Maxwell's equations in spherical geometry and are characterised by four indices [38], which characterise the spatial symmetry of the corresponding eigenwaves. It was demonstrated in Ref. [38] that a micrometre-sized droplet of the NLC 5CB functions as a tunable optical cavity, and the light is resonantly circulating inside the droplet by subsequent TIR at the NLC–water interface. Because the interface is very smooth, as it is stretched by the surface tension, the optical resonances in a NLC microdroplet are very sharp, which means that the Q-factors of these resonators are rather high, of the order of 10,000. In that case, the tuning was realised by applying an external electric

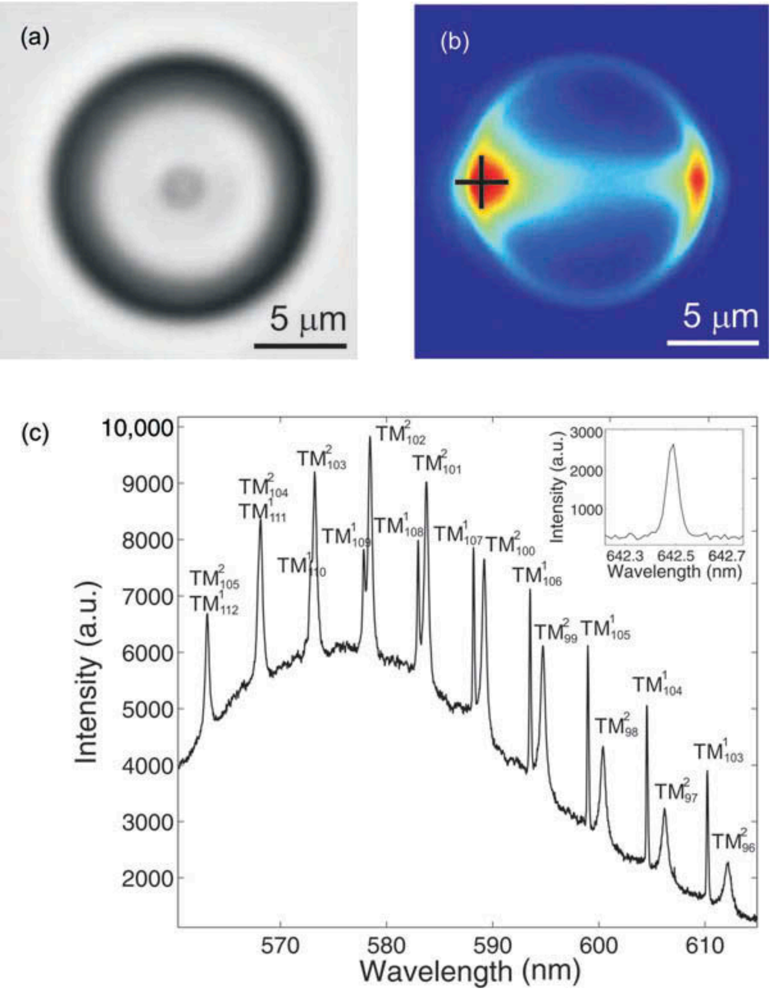

Figure 4. (Colour online) Light in liquid crystal microdroplets. (a) Microdroplet of nematic liquid crystal E12 in PDMS. (b) Detected light intensity under illumination by strongly focused beam of the Ar^+ laser tweezers, illuminating the submicron-sized spot near the rim of the droplet, indicated by the black cross. Because fluorescent dye is added to the NLC, WGMs are visible as a bright rim inside the droplet. (c) Spectrum of WGMs in 12.6 μm radial nematic droplet. The inset shows details of a WGM spectral line in a 53 μm diameter E12 droplet. The linewidth is approximately 0.055 nm [38] (image courtesy of M. Humar).

field, which causes elastic deformation of the nematic director in the droplet's interior and therefore changes the optical path for the resonant modes. This results in the electric field-induced resonance mode shifting, which is nearly two orders of magnitude larger than in solids. In solid-state WGM microcavities, the resonances are usually tuned by heating or cooling the optical microdevice and the energy dissipation needed for tuning is the main drawback for the application of solid-state photonics. In contrast, tuning is performed by the electric-field effect in the NLCs, which decreases the energy consumption of the LC photonic devices compared to the solid state or orders of magnitude.

The idea of assembling photonic devices by simply dispersing LCs in immiscible fluids was further developed in 2010 [39], when we have demonstrated the operation of the first microlaser, based on chiral NLC dispersion. A small amount of a fluorescent dye was added to the chiral NLC, and this fluorescent and chiral NLC was further dispersed in water with added surfactant that assured tangential orientation of the NLC molecules at the NLC–water interface. In a fraction of a second, millions of droplets with onion-like internal structure were self-assembled, as shown in Figure 5. In each droplet, a helical arrangement of NLC molecules was induced by chiral dopants and the resulting helical structure is evolving from the centre of the droplet towards its surface. In photonics, such a structure is known as the spherical Bragg-onion resonator and because of the spherical symmetry, it has an omnidirectional band gap. This means that the light of the frequency, which is in the forbidden gap of the chiral nematic structure, is reflected back to the centre of the droplet whenever it travels radially outwards.

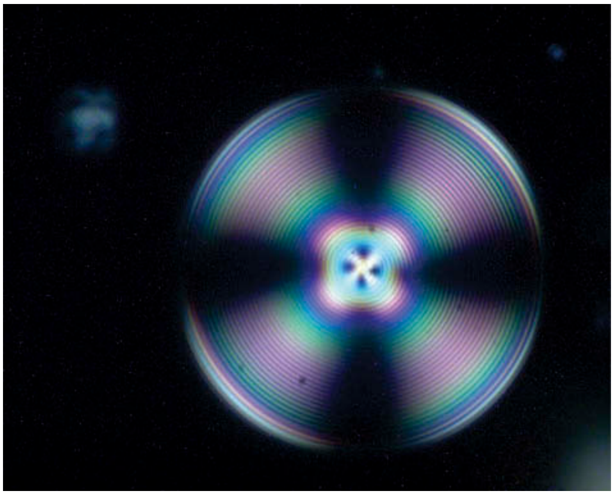

Figure 5. (Colour online) Onion-like structure of a long-pitch cholesteric liquid crystal droplet in glycerol. This structure exhibits an omni-directional photonic band gap for one circular polarisation of light (image courtesy of M. Humar).

However, as we have the fluorescent dye inside the droplet, the back-scattered or Bragg-reflected photon induces a stimulated emission of light from the optically excited dye molecules. By increasing the pumping energy, lasing of the droplet is achieved above some threshold, as shown in Figure 6.

Because the band gap is omnidirectional, so is the lasing. A chiral nematic microdroplet is therefore an omnidirectional laser and it emits a coherent laser light uniformly in full space. It was reported in the original experiments [39] that the light from this laser is not polarised, although it is expected that the laser emission be circularly polarised, as observed in many lasing experiments on thin chiral NLC layers. So far, several additional experiments have been inconclusive, although weak circular polarisation was observed in some of the experiments.

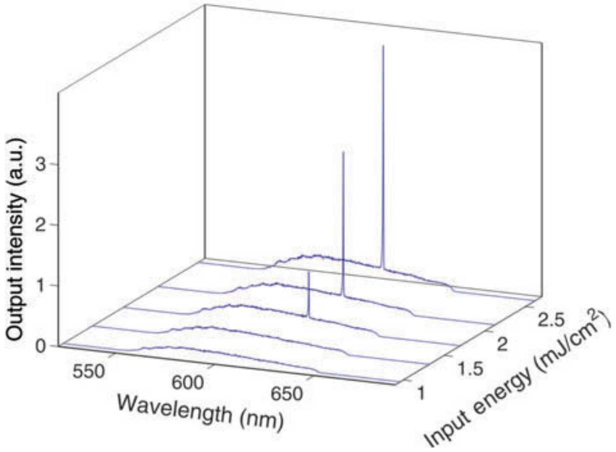

Figure 6. (Colour online) Lasing spectra of a microdroplet of MLC-7023 liquid crystal with 25.5 wt% of S-811 chiral dopant and 0.2 wt% fluorescent dye 7-diethylamino-3,4-benzophenoxazine-2-one (Nile red, Sigma-Aldrich) in glycerol at different energies of the pumping pulse. The threshold for lasing is at ~1.8 mJ/cm^2 (image courtesy of M. Humar).

The 3D chiral nematic microlaser is a dye-laser and is excited by a short (nanosecond) pumping laser pulse, which excites the electrons in the dye molecules to their upper energy levels. Both the excitation and laser emission take place at a nanosecond time scale, as shown in Figure 7, which means that in principle such a laser could process light at the gigahertz frequencies. It has also been demonstrated that these self-assembled pulsed microlasers could be polymerised [40,41] and even deposited on solid surfaces as some sort of the laser-paint [40]. Recently, we have demonstrated [42] pulsed lasing in the WGM regime, which emits light into the equatorial plane.

The chiral NLC microlaser is mechanically a very robust device, although it is made of a liquid. This is demonstrated in Figure 8, where a small droplet of the chiral NLC, embedded in the polydimethylsiloxane (PDMS), is punched by an optical fibre, to make an optical output of the resonant light into the fibre. It is clearly seen from panel (B) that the laser is still operating even under such severe conditions with huge elastic deformation and local fracture. It is beyond imagination that anything like that could be realised using solid state materials. On the other hand, a chiral NLC microlaser suffers from the defectiveness that are characteristic of the dye-lasers: (i) a decreasing of the lasing intensity with time, which is due to the electronic transitions into the triplet, dark states, (ii) a chemical deterioration due to the dye decomposition, induced by a strong light. It is currently estimated that LC

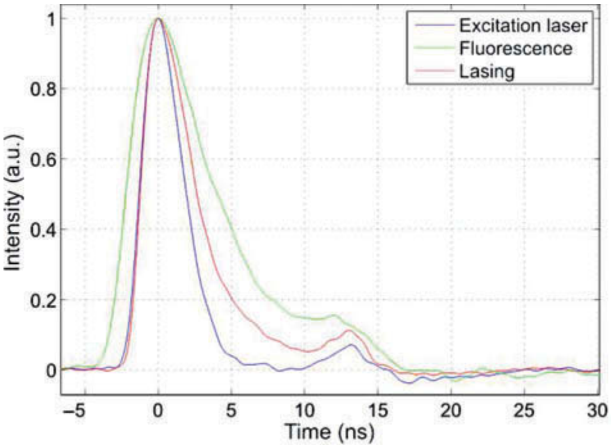

Figure 7. (Colour online) Nanosecond response of the 3D cholesteric microlaser (image courtesy of M. Humar).

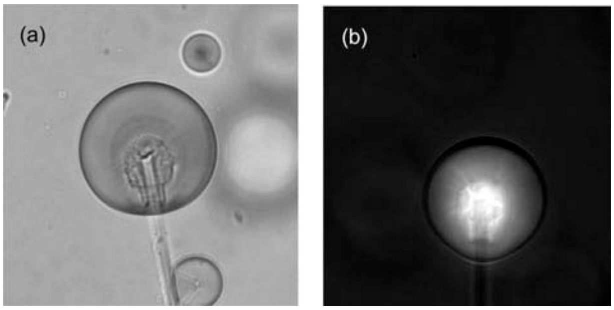

Figure 8. Coupling of a 3D cholesteric microlaser to an optical fibre. (a) The cholesteric droplet, which forms the laser, is punched by an optical fibre right to the centre. (b) The microlaser is still operating normally, although it has been severely damaged by the fibre and its shape has been distorted (image courtesy of M. Humar).

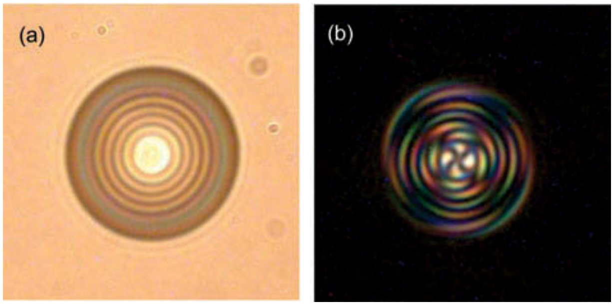

Figure 9. (Colour online) A microdroplet of a long-pitch ferroelectric smectic liquid crystal SCE-7 in PDMS observed with no polarisers (a) and between crossed polarisers (b). In a ferroelectric microlaser, the emission wavelength could be tuned by external DC electric field (image courtesy of Huang Peng).

microlaser can emit around one million pulses before bleaching. This is clear evidence that further efforts have to be performed towards improvement of the laser's stability.

The discovery of the LC optical microresonators and microlasers opened some fundamental dilemmas regarding the photonics based on the LCs. The first question is to what extent do we really need the nematic colloidal crystals to assemble microphotonic LC devices? It is clear that many of the photonic functions, such as tunable optical filtering and laser emission, could be realised using simple procedures in microdispersions of different LCs in water. This means that we do not need to perform delicate assembly of 3D photonic crystals from the nematic colloidal particles of 200–500 nm size. Instead, the function of the photonic crystal and its band gap-based optical filtering could be obtained in a single droplet of a properly designed LC phase, where millions of identical devices could be produced in a fraction of a second. We could then use the forces between colloidal inclusions to assemble these fluid microelements into firmly bound superstructures. It is still an open question, what kind of microdevices could be self-assembled form LC dispersions, and we shall briefly address this speculative question in the next section.

LC microlasers, microresonators and self-assembled optical fibres

NLC microlasers and tunable microresonators in a form of freely suspended microdroplets are two examples of truly self-assembled photonic microstructures. Here, the self-assembly is realised on a micrometre scale by the surface tension that promotes spontaneous formation of microdroplets. On a molecular level, chiral nematic phase of LCs leads to the spontaneous formation of droplets with intrinsic helical interior organisation, while in non-chiral materials, perfect radial structures are obtained.

It is tempting to imagine that spherical microlasers and other photonic microdevices could be made from other chiral phases, such as the chiral smectic ferroelectric materials (see Figure 9). In this case, the emission wavelength of the dye-doped ferroelectric microlaser could be tuned via the linear coupling of the external electric field to the spontaneous electric polarisation. It would be interesting to see what is the tuning range and the reversibility of the electric-field-tuning in chiral nematic Bragg 3D microlasers, using the dielectric coupling that is quadratic in the electric field. Furthermore, it would be interesting to study microdroplets of the blue phase materials that themselves exhibit 3D photonic (incomplete) bandgap, as evidenced from the lasing experiments of Cao et al. [43].

The surface tension between two immiscible liquids provides the formation of microdroplets of a perfect spherical shape that could be used as an optical cavitiy for tunable resonators, optical filters and lasers. The question is whether photonic objects of another shapes could be self-assembled, such as the fibres [44], toroids etc. It is clear that in this case one has to be able to engineer the surface tension versus the elasticity of the LC. While in spherical objects the surface energy of the LC in the carrier fluid dominates the elastic energy of its deformed interior, lowering the surface energy could result in the formation of elongated, fibre-like objects. This is, in fact, well known in diblock polymers [45], where elongated fibre-like objects called myelin figures are well known. Similar objects were reported by Prathiba et al. [46] in binary mixtures of LCs. It was demonstrated recently [47] that smectic A LC forms filaments when dispersed in water with CTAB added. These results are clear evidence that bodies of complex shape and topology could be self-assembled in LCs in the future.

Structuring of LCs on a microscale to assemble liquid microdevices

Modern devices based on LCs, such as screens and modulators are using thin layers of LCs with substantial lateral sizes up to the order of a metre. Their primary function is visualisation of information and this determines their size, the internal structure and organisation. We propose another class of future LC devices that are the liquid analogue of solid state microcircuits. The function of these devices would be processing the information on a microscale, much as the information is nowadays processed in solid state microelectronic circuits. These devices would be made of different LCs, structured in functional microelements and firmly bound together into functional unities with the structural forces, provided by LCs themselves. Unlike electric currents in microelectronic devices, these devices would use the currents of photons to transmit the information at the speed of light. Unlike planar geometry that is used in the design and production of modern microelectronic circuits, these devices could be organised in 3D because of their fluidic nature. One could imagine that combining simple organic materials like LCs, with biomaterials, might lead to a programmable self-assembly of complex microdevices that would be capable of growth, self-repair and self-healing. It is clear that in order to achieve these goals several key fundamental problems are to be solved.

- ***New LC materials*** have to be synthesised that are not miscible between themselves. These new immiscible materials would provide the basis for the 3D microstructuring of LCs. Suppose we have a nematic material A that is immiscible with another nematic material B. This would allow to make a dispersion of droplets of the nematic A in the nematic B. Using the surface engineering one could provide homeotropic anchoring of the nematic B on the spherical surface of the nematic A. This would allow us to entangle arbitrary number of droplets of the nematic A using the topological defect loops formed in the nematic B. Finally, these two materials could be knotted and linked into arbitrary 3D all-liquid structures using the entanglement mechanism that we know from the nematic colloids.
- ***Surface engineering and topology***. The variety of geometrical shapes that spontaneously form in the LC dispersion is limited to spheres and fibres of LCs. The synthesis of a new class of immiscible LCs would address several questions on their surface tension. For example: (i) what is the anchoring of one LC on another LC? Can we engineer arbitrary combinations of their mutual surface alignments, such as a planar alignment of the nematic A on a planar alignment of the nematic B, planar A on homeotropic B etc . . . (ii) Could we engineer the surface energy so that we would induce spontaneous formation of tori-like objects of nematic A in the nematic B? Are other topologically non-trivial objects that could be formed by surface tension engineering? (iii) What is the transfer of topological defects across the liquid–liquid interface? One can see already from these few questions that there is an immense new field of surface physics and chemistry with anisotropic liquid interfaces.
- ***Microstructuring and topology of solid–liquid interfaces***. If we continue along the hypothesis that we are able to microstructure immiscible LCs into 3D architectures, the question is how to confine these all-liquid structures into a kind of compartment made of solid walls. These walls should not only serve as a confining boundary, but must also have a topological role. Namely, microstructuring of immiscible LCs requires not only a well-defined surface anchoring, but most likely also the surface-structuring or surface-patterning of the orientational order. This surface patterning will most likely be accompanied by various surface topological defects, which delineate the regions with a different kind of surface anchoring. These topological defects could serve as the sources of the surface forces that could provide surface binding of LC microstructures. However, one could also deliberately create artificial sources of topological defects using, for example, precise 3D two-photon polymerisation technique, see [48]. An example of a microstructure manufactured on a glass surface is shown in Figure 10. These topological anchors or 'handles' could be used to mechanically stabilise all-LC structures by providing the surface forces via defect entanglement etc.
- ***Resonant transport and control of light in microstructured LCs***. Although the operation of basic photonic microdevices has been successfully demonstrated, it remains to demonstrate that the transport of light between different photonic elements made of LCs is possible. Furthermore, as the aim is to develop all-photonic devices, where the flow of light should be controlled by photons rather than electrons, new concepts of light control in LCs have to be developed. We have recently demonstrated [49] that light could be resonantly transferred from a planar polymer waveguide into the optic microcavity made of a NLC droplet with a radial internal structure. The geometry of the device for the demonstration of resonant light transfer is shown in Figure 11. It comprises of a

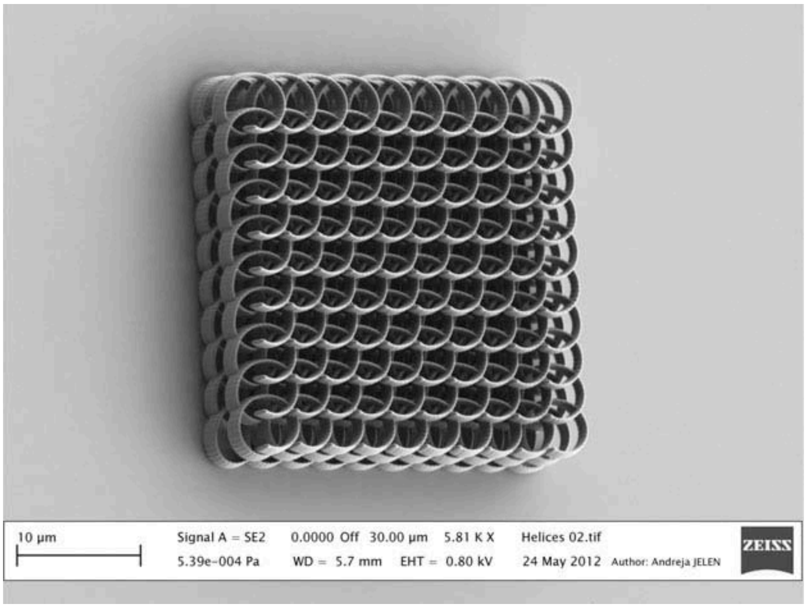

Figure 10. An example of 3D chiral structure that was manufactured using 3D two-photon polymerisation technique using Nanoscribe Photonic Professional system. (image courtesy of M. Humar).

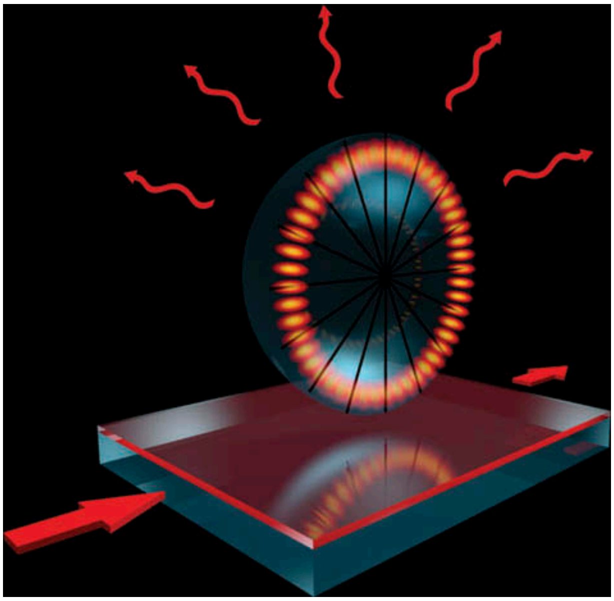

Figure 11. (Colour online) Schematic drawing of resonant light transport between a planar waveguide deposited on glass substrate and the spherical nematic LC microcavity. The spectrum of the resonantly circulating light is measured by spectral analysis of light, leaking from the microcavity (image courtesy of M. Humar).

polymer waveguide on a glass substrate that can transport the input light (red arrow in Figure 11) in a finite number of electromagnetic eigenmodes. A small droplet of a NLC with a radial structure is suspended in aqueous solution, floating just above the upper surface of the polymer waveguide. Once proper conditions are met, such as close proximity of the droplet and the waveguide, the light is resonantly transferred from the polymer waveguide into one (or several) resonant WGMs, sustained by the NLC microdroplet. These resonantly transferred modes could be observed [49] simply by analysing the spectrum of light emitted from the droplet. The demonstration of the resonant light transport from a planar optical waveguide into the liquid crystalline microcavity is the first direct proof-of-the-concept of LC microphotonic circuits. The analysis shows [49] that as much as 50% of light energy confined into micrometre-sized area close to the droplet contact point could be resonantly transferred into the microcavity with an optimum choice of the refractive indices and mode-matching conditions. In this case, the energy transfer depends exponentially upon the droplet-surface separation, because the mechanism of the energy transfer implies both the spatial and temporal overlapping of the evanescent and exponentially decaying tails of the modes inside the planar waveguide and the spherical microcavity.

Why topology matters in crystal colloids and multiple dispersions?

The concept of integrated microphotonics based on LC multiple dispersions implies the use of a multitude of small, micrometre-sized objects self-assembled from ordered fluids or complex soft matter. In this case, it is not just only the geometry of the compartment, where the fluid is confined, that is important, but the topology of the confined fluid as well. The confinement (in case of micro droplets) of an ordered fluid, or the insertion of a foreign object into the ordered fluid, always induces formation of topological defects, which occupy a considerable part of the fluid because of the smallness of the system. Their presence not only considerably changes the energy of the system in view of considerable amount of the elastic energy, stored in defects, but has a strong influence on the performance of microdevices, because of the conservation of the topological charge.

For example, switching of the interior of the LC microdevice is constrained by the inevitable conservation of topological defects at all times. On the other hand, topological defects are the generators of mechanical forces between the inclusions in LCs and are responsible for a variety of structural motifs of colloidal structures, observed in various LC dispersions. By tailoring the positions and type of topological defects, one could, in principle, devise a variety of microstructures in LCs with a variety of different functions, such as optical signal filtering, steering and multiplexing. It is therefore likely that topological properties will be very important in designing and producing any future integrated LC microdevice, based on multiple LC dispersions. This is in sharp contrast with existing hard-matter microdevices, where only the geometry of the device is important, and the topology is of a minor importance.

We believe that future explorations of the topological properties of multiple liquid crystalline dispersions (featuring multicomponent and immiscible LCs and solid particles) together with the analysis of the topological laws that seem to imprint the topology of matter onto the topology of EM waves, interacting with topological matter will be of outmost importance in the future. Recent results, such as the transformation of a Gaussian beam into a Laguerre–Gausian beam after passing through the topological defect in the NLC [50] or a toron [51] imprinted into a frustrated chiral NLC are clear indications of this phenomena and could lead to interesting results in the future. Explorations of the limits of the variety of topological entities that could be created in LCs are also very promising, as they have led recently to fundamental observations, such as knotting and liking of a LC ordering field and recent observation of the Hoph fibration [52], to mention only a few.

In conclusion, there are strong indications that we could use the fascinating topological variety and flexibility of LCs not only to explore realisations of topology in Nature, but also to use these phenomena for engineering of novel microphotonic devices based exclusively on soft matter. The unusual combination of the softness and fluidity of LCs, combined with rich topology that generates forces between constituents might be of considerable interest in the future.

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