

Uniaxial Strain-Controlled Laser Emission Tuning from Polymer-Matrix-Embedded Laser Dye-Doped Cholesteric Liquid Crystal Microdroplets

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Abstract—We fabricated a polymer matrix containing cholesteric liquid-crystal-doped laser-dye microdroplets. Under uniaxial mechanical deformation, the polymer-matrix-embedded microdroplets tune their shape and optical parameters, as confirmed by polarized and fluorescence optical microscopy. Using a laser-pumping source, we stimulated laser emission from the microdroplets. In addition, we showed that polymer-supported, laser dye-doped cholesteric liquid-crystal microdroplets exhibit corresponding tuning of laser emission under uniaxial mechanical strain. In our experiments, we observed strain-stimulated tuning of laser lines over 45 nm of the optical spectrum.

The dual nature of liquid crystals, which combines the anisotropic material properties of solids with the fluidity of liquids, makes them ideal for many photonic applications [1]. Cholesteric liquid crystals (CLCs) exhibit a helical modulation of the director with pitch p , creating a photonic band gap (selective reflection band) centered at a wavelength. For a short CLC pitch, the structure exhibits Bragg reflection at wavelength $\lambda = np \cos \phi$ and, at normal incidence, this simplifies to $\lambda = np$, where p is the helical pitch of a CLC. The refractive index is calculated as $n = (n_e^2 + n_o^2)^{1/2}$, where n_e and n_o are the extraordinary and ordinary refractive indices, respectively. Using CLCs as a non-miscible, oil-like soft-matter substance to spontaneously form a spherical microcavity with a radially modulated refractive index, we can realize a 3D Bragg cavity that minimizes surface area for a given material volume. CLCs in complex geometries, particularly droplets and shells, have garnered significant attention [2]. Within the band gap, the photonic density of states is suppressed, while it is strongly enhanced at the band edges. When a laser dye is added and optically pumped, amplified spontaneous emission is funneled into these edge modes, leading to narrow-line, mirrorless lasing. Various internal and external influences, such as temperature, electric fields,

and light, can alter the tuning of laser emission in CLC microdroplets [3–7]. In this work, we present uniaxial-strain-controlled, tunable lasing from laser dye-doped CLC (LDCLC) microdroplets (40–60 μm) emulsified in a polymer matrix.

The experiments used the liquid crystal BL-090 as the nematic matrix, with optical anisotropy $\Delta n = 0.28$ and dielectric anisotropy $\Delta \epsilon = +20.6$. We used MLC-2011 as the chiral dopant and Coumarin 6 (C6) as the laser dye (LD) and gain medium. We used poly(vinyl alcohol) (PVA) with an average molecular weight of 45,000–70,000 as the polymer matrix. All materials were purchased from Merck. The final LDCLC mixture was prepared with the following concentration ratios: 99.7 wt% [(68 wt% BL-090 + 32 wt% ZLI-811) + 0.3 wt% C6]. We stirred the LDCLC mixture in the isotropic phase at 95°C and 450 rpm for 5 minutes to ensure thorough mixing. We prepared the PVA solution at 92 wt% water + 8 wt% PVA. The PVA/LDCLC film was prepared by incorporating 5% LDCLC into the PVA matrix. We stirred the PVA/LDCLC solution at 250 rpm for 5 minutes at room temperature and poured it onto a glass plate cleaned with deionized water. The PVA/LDCLC film was dried at room temperature for 48 hours. After drying, we carefully peeled the film off the glass surface. The resulting film contains LDCLC microdroplets emulsified within the PVA, with an average size of 40–60 μm . We used a polarizing optical microscope and a fluorescence microscope equipped with a CCD camera to observe the DDCLC microdroplets. For optical excitation, we used a Nitrogen laser (MNL-100) with $\lambda = 337.1$ nm and a 3 ns pulse duration at 5 Hz. We collected the emitted laser line spectra using an optical fiber-coupled spectrometer (Ava-Spec AVS-2048-2) with a resolution

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of 1 nm. To record mechanical uniaxial strain-controlled laser emission tuning, we fabricated a film strain device in our laboratory.

We first investigated the absorption and fluorescence emission spectra of C6 dissolved in the CLC medium to establish the dye's spectral compatibility with the optical excitation source and the CLC photonic structure. Figure 1 shows the absorption and emission spectra of C6.

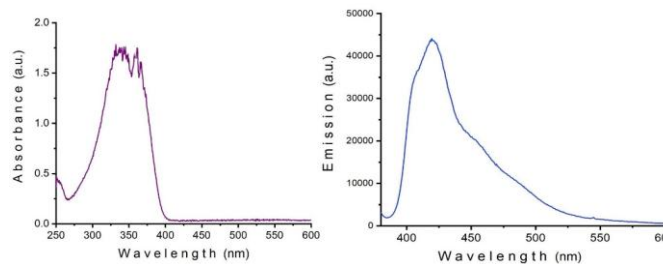


Fig. 1. Absorption and fluorescence emission spectra of C6 dissolved in the CLC medium.

C6 absorbs in the ultraviolet/blue region of the optical spectrum, enabling efficient excitation by the 337.1 nm nitrogen laser. Following excitation, an LD produces broad fluorescence that can interact with the photonic density of states of the CLC. Without photonic feedback, the LD emission is expected to retain the broad spectral characteristics associated with molecular fluorescence. In the CLC environment, however, the periodic helical structure modifies emitted-light propagation. The overlap between the LD emission band and the CLC photonic band structure permits preferential amplification of selected spectral components. This interaction between optical gain and distributed feedback underlies the observed narrow-band laser emission. We investigated the morphology and optical characteristics of the LDCLC microdroplets embedded in a PVA matrix using polarized optical and fluorescence microscopes equipped with a CCD camera. First, we recorded images of both the strained and non-strained PVA/LDCLC composite films using polarized optical microscopy (Fig. 2).

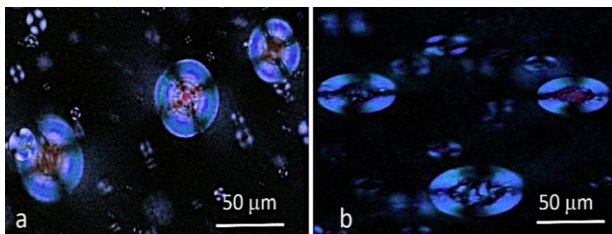


Fig. 2. Non-strained PVA/LDCLC composite film observed using polarized optical microscopy (a). Image of LDCLC microdroplets embedded in the PVA matrix under uniaxial mechanical deformation (b).

In a CLC with the helical axis perpendicular to the film, the helical pitch p scales approximately linearly with film thickness under strain. Because thickness changes linearly

with imposed strain in the rubbery, incompressible regime, the pitch-strain relation is effectively linear over a wide range. The difference between the unstrained and strained states indicates that mechanical deformation of the polymer matrix affects the internal optical structure of the CLC droplets. These changes may arise from droplet deformation, reorientation of the CLC director, changes in helical pitch, or a combination of these effects. The approximate Bragg relation explains the optical behavior at normal incidence for $\lambda = np$. Consequently, a change in the helical pitch p produces a corresponding displacement of the photonic band gap. If the refractive-index contribution remains approximately constant over the deformation range, the relative wavelength change can be approximated as $\Delta\lambda/\lambda \approx \Delta p/p$. Thus, mechanical deformation directly modifies the spectral position of the CLC photonic structure. Figure 3 shows PVA matrix-embedded LDCLC microdroplets under both unstrained and strained conditions, as viewed under a fluorescence microscope.

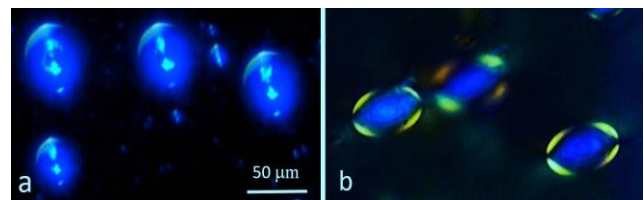


Fig. 3. Strained (a) and non-strained (b) LDCLC microdroplets as seen under a fluorescence microscope.

Figure 4 shows the experimental setup used to demonstrate laser-line tuning under uniaxial strain in the PVA-embedded LDCLC. A pumping beam from a nitrogen laser (1) excites an LDCLC microdroplet localized in the PVA polymer matrix, causing it to emit a laser line. Mechanical stretching of the LDCLC polymer film (2) uniformly and continuously elongates the LDCLC microdroplets using a stretching device (3), causing a corresponding continuous shift of the emitted laser lines toward the short-wavelength region of the spectrum. This process is observed via the spectrometer (4) connected to the computer (5).

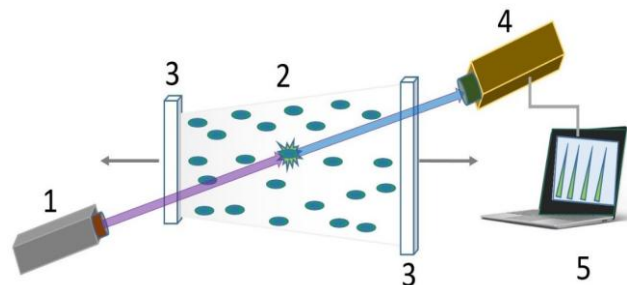


Fig. 4. Experimental setup: Nitrogen laser (1), PVA/CLCP film (2), stretching device (3), Fiber-equipped spectrometer (4), Computer (5).

Under 337.1 nm optical excitation, the LDCLC microdroplets exhibited narrow-band laser emission. The emission arises from optical amplification of the LD fluorescence within the CLC distributed-feedback structure. The emission spectrum was tuned when the composite film was mechanically stretched. Under uniaxial stress, the photonic band gap shifts to shorter wavelengths as the CLC helix contracts. The pitch change is reported to be linear with film thickness, enabling mechanically tunable band-edge lasing over a 45 nm range (Fig. 5).

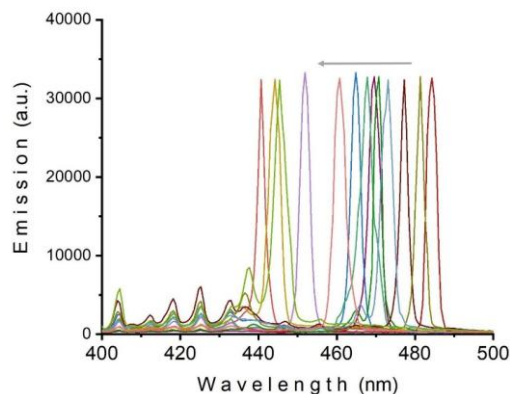


Fig. 5. Mechanical strain-dependent laser emission tuning from a PVA/CLCP film.

The laser emission spectra of the PVA/LDCLC composite film were recorded at different uniaxial strain levels and showed a shift in the laser emission wavelength. This spectral shift shows that the lasing wavelength is mechanically tunable. Unlike thermal tuning, in which the CLC pitch and refractive index change with temperature-dependent changes in molecular order, the present approach uses mechanical deformation of the polymer-supported microdroplet structure. Embedding LDCLC microdroplets in a PVA matrix offers several advantages over a conventional liquid-crystal cell. The composite film is mechanically flexible and can be manipulated without requiring rigid substrates. The CLC phase remains confined within microscopic domains, while the polymer matrix provides structural support. This enables macroscopic deformation and allows investigation of its effect on microscopic photonic structures. In addition, the distributed-feedback mechanism eliminates the need for conventional external laser mirrors. The CLC itself provides the periodic optical structure required for spectral selection and feedback. The combination of mechanical flexibility, optical gain, and self-organized photonic feedback makes the resulting material attractive for strain-responsive photonic devices. The results show that mechanical deformation can serve as an external control parameter for CLC distributed-feedback laser emission. The polymer-embedded architecture provides a flexible platform for strain-responsive photonic devices. It

may be particularly useful for mechanically tunable optical sensors, flexible lasers, optical switching elements, and wearable photonic systems. Future work should quantitatively correlate applied strain with laser wavelength shift, determine tuning sensitivity, and establish the contributions of microdroplet deformation, director reorientation, and pitch variation to the observed spectral response.

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