

Nearly unpolarized and linearly polarized laser generation from dye-doped cholesteric liquid crystal laser using a mirror reflector

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ABSTRACT

Usually when optically pumped, dye-doped cholesteric liquid crystal (CLC) laser generates circularly polarized laser light in the same handedness as the cholesteric helix. On a distributed feedback basis, laser light at photonic band edge comes out from both sides symmetrically. In this work, we incorporated a metallic mirror reflector to the CLC laser on one side so that laser light only emits from single direction and hence the extracted output can be enhanced by ~2-5X. Furthermore, upon reflection the mirror reflector introduces a π phase change. Therefore, two different types of CLC lasers with different polarization states are demonstrated by putting the mirror at different substrates. With a mirror attached at the outer side of the liquid crystal substrate, we obtained a nearly unpolarized CLC laser based on incoherent supposition of two orthogonal circularly polarized beams. With mirror coated at one of the inner surfaces of the liquid crystal cell, we obtained a linearly polarized CLC laser based on coherent combination of two orthogonal circularly polarized beams. For these two cases, the output power and polarization states are compared and the physical mechanism is discussed correspondingly. Moreover, the tuning of the linear polarization direction is demonstrated.

Keywords: Cholesteric liquid crystals, laser, metallic mirror reflector, linearly polarized light

1. INTRODUCTION

Cholesteric liquid crystals (CLC) have been widely used in liquid crystal full color displays, bistable displays, light shutters, tunable color filters and so on. In recent years, the photonic properties of cholesteric liquid crystal have also attracted tremendous interests from both scientific and technological viewpoints [1]. In CLC planar structure, the LC molecules are self-organized into a helical structure with its helical axis perpendicular to the glass substrates. When the linearly polarized light propagates through the medium, it experiences alternating ordinary and extraordinary refractive index. Bragg reflection can be established if the number of pitches is enough. Hence the circularly polarized light in the same handedness with cholesteric helix will be reflected and the opposite one will be transmitted as it passes through the CLC medium. The reflection band can be accurately determined according to simple relationships as $\lambda_0 = \langle n \rangle \cdot p$ and $\Delta\lambda = \Delta n \cdot p$, where λ_0 and $\Delta\lambda$ represent the central wavelength and bandwidth of the reflection band, and Δn and p represent the LC birefringence and cholesteric intrinsic pitch length [2], respectively. Such a selective reflection band corresponds to a forbidden band in photonic crystals where the

photons cannot propagate through, known as the photonic band gap. Regarded as one-dimensional photonic crystal, CLC provides possibilities for trapping the photons and shaping the density of states [3]. Therefore, when the active medium is doped into CLC, it opens a new way in generating laser light with low threshold at its photonic band edge [4, 5] or at its defect layers [6, 7]. Due to the periodic modulation of refractive index, the CLC provides distributed feedback in the band edge lasing while it functions as a Bragg reflector in defect mode lasing. The main features for CLC-based lasers include mirrorless lasing and tuning feasibility, etc.

Because the reflection in CLC is only induced for circularly polarized light, the laser emission generated from CLC photonic band edge laser is also circularly polarized. Typically the laser emission is emitted from both sides as a result of structure symmetry. In practical use, only the emission from one end can be fully utilized and the emission from the other side is wasted. In this paper, we put a metallic mirror reflector onto the CLC laser which reflects the emission coming from one end back to the other. Furthermore, the interesting phenomenon takes place because the mirror introduces a π phase change so that the polarization state of the output emission is converted into either nearly unpolarized or linearly polarized light depending on which layer the metallic mirror is inserted. The control of the output linear polarization direction is also demonstrated, which proves to be very useful in the polarization manipulation and control.

2. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

In experiment, our CLC mixture consists of nematic liquid crystal host BL006 ($n_e=1.78$, $\Delta n=0.28$, from Merck) and right-handed chiral agent MLC6248 (Helical twist power= $11.1\mu\text{m}^{-1}$, from Merck) or CB15 (Helical twist power= $7.7\mu\text{m}^{-1}$, from Merck). As the active material, the highly emissive laser dye: 4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminoethyl)-4H-pran (DCM, from Exciton) at 1.5% weight concentration was doped into the CLC host. After thoroughly mixed, the whole mixture was capillary filled into the empty LC cell which had ITO coating and polyimide alignment layers on both substrates. The alignment layers were rubbed in anti-parallel directions and the pretilt angle was small ($<3^\circ$). A slow cooling process gave rise to a cholesteric liquid crystal phase in planar structure. A specially designed LC cell with Aluminum (Al) coated on one of the inner surfaces instead of ITO layer was used for generating linearly polarized laser light.

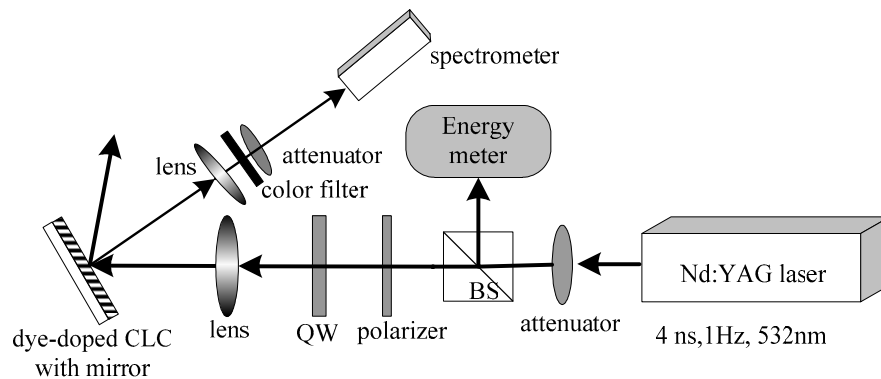


Fig. 1. The experimental setup of a CLC laser. BS: beam splitter, QW: quarter-wave plate.

Figure 1 shows the experimental setup. As the pump source, Nd -YAG (Minilite II, Continuum,) laser was operated at $\lambda=532$ nm, 4 ns pulse width and 1 Hz repetition rate. The pump beam was separated into two beams with one of them monitored by the energy meter (Laserstar, Ophir) and the other focused into the lasing cell at $\sim 30^\circ$ oblique incidence. The pump beam was changed into left handed circularly polarized light using a polarizer and a broadband quarter wave plate. Because the reflection band shifts to shorter wavelength as the incident angle increases, the circularly polarized pump beam in the opposite handedness with the cholesteric helix would help reduce the band gap reflection of the pump light as compared to using a linearly polarized pump. On the lasing cell, the pump beam spot was estimated around 200 μm in diameter. A metallic mirror reflector can be put at the outside surface of the CLC cell to reflect the emission back into the cavity for generating nearly unpolarized emission. The laser emission was collected by another lens into a fiber-based spectrometer (HR2000 with resolution =1 nm, Ocean Optics). The circular polarization state of the output was detected by a CLC filter with its reflection band covering the lasing wavelength.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Transmittance of the CLC laser and the laser emission spectrum

We first measured the reflection band of the CLC laser, as shown in Fig. 2. As an example, the corresponding lasing spectra of the CLC laser with nearly unpolarized output and linearly polarized output are also included in Figs. 2(a) and 2(b), respectively. It is noticed that lasing actions take place at the long wavelength band edges, which are within DCM fluorescent range. The shorter wavelength band edges are obscured by the DCM absorption. The lasing spectrum is centered at wavelength $\lambda=635$ nm for Fig. 2(a) and $\lambda=601$ nm for Fig. 2(b). The FWHM (full width of half maximum) of laser line is around 1 nm, limited by the resolution of our spectrometer.

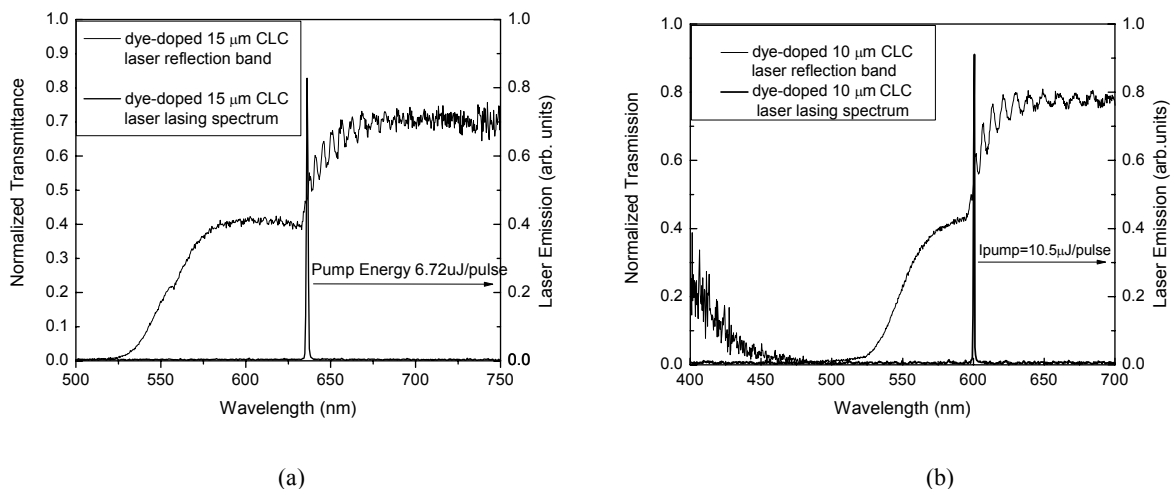


Fig. 2. (a): the reflection band of a 15- μm -thick dye-doped CLC laser using mixture BL006 and 38% CB15, and the lasing spectrum pumped at 6.72 $\mu\text{J}/\text{pulse}$ with nearly unpolarized output; (b): the reflection spectrum of a 10- μm -thick dye-doped CLC laser using mixture BL006 and 27.3% MLC6248, and the lasing spectrum pumped at 10.5 $\mu\text{J}/\text{pulse}$ with a linearly polarized output.

3.2 Nearly unpolarized laser emission

When the metallic mirror is attached to the CLC laser at the outer surface of one glass substrate in optical contact, lasing performance is measured as Fig. 3 shows. This experiment is performed using the sample with BL006 and CB15 mixture, whose reflection band is shown in Fig. 2(a).

The solid line with filled circles, the dashed lines with open triangles, and the dashed lines with open circles represent the total laser emission, right-handed circularly polarized (RCP) component, and left-handed circularly polarized (LCP) component with mirror attached, respectively. The solid line with filled squares describes the original total laser output with no mirror reflector. Results here indicate that with a mirror reflector attached the laser output is increased by $\sim 2X$ and the polarization is nearly unpolarized. Among the total output, $\sim 60\%$ is RCP and $\sim 40\%$ is LCP. Because the metallic mirror brings in a π phase change, when reflected back, the RCP is changed into LCP with some reflection loss involved. For the right handed CLC lasing cell, the reflected part will directly propagate through, contributing to the 40% LCP light in the total output. There is no obvious linear polarization direction observed in the total output. That means the original part and the reflected part are combined based on incoherent superposition. Hence by using a mirror reflector, a nearly unpolarized CLC laser is obtained [8].

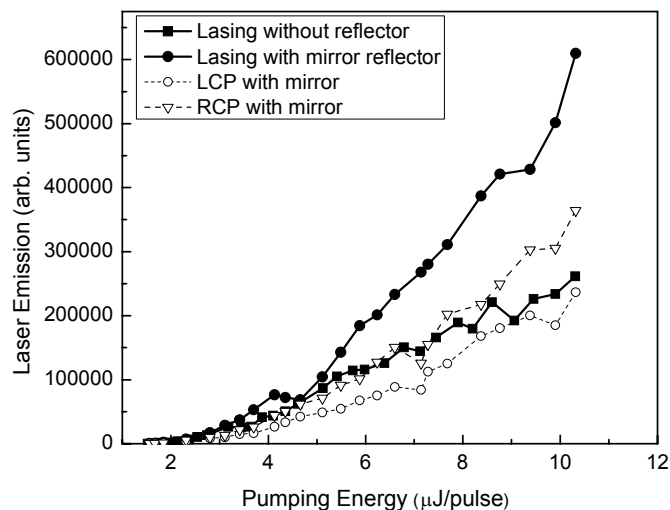


Fig. 3. Pump energy dependent laser emission with a mirror reflector at outer surface. Solid lines with filled circles and filled squares represent the total lasing output power with and without the metallic reflector, respectively. Dashed lines with open circles and open triangles represent the LCP and RCP component with the metal mirror reflector.

3.3 Linearly polarized laser emission

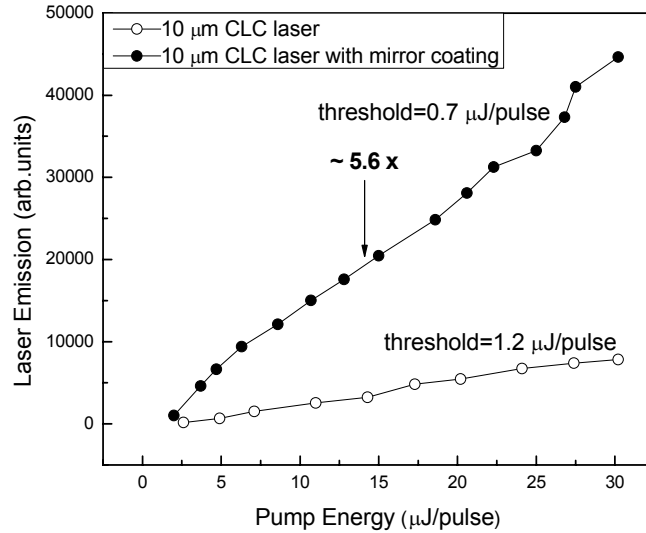


Fig. 4. Pump energy dependent laser emission from a 10- μm normal CLC laser cell (open circles) and a CLC laser with one inner surface coated with metallic mirror (filled circles).

With a metallic mirror coating on the inner surface of the CLC cell, the generated laser emission is linearly polarized rather than circularly polarized. This experiment is performed using BL006 and MLC6248 mixture, whose reflection band is shown in Fig. 2(b). In this case, the output emission is remarkably enhanced, as shown in Fig. 4. Using a normal 10- μm CLC laser, the pump energy dependent lasing output power is shown with open circles. With mirror coated on the inner surface, the emission is shown with filled circles. The corresponding threshold is decreased by nearly 2X (from 1.2 $\mu\text{J}/\text{pulse}$ to 0.7 $\mu\text{J}/\text{pulse}$). Considering that the normal CLC laser emits photons from both sides rather than single side as the mirror reflective CLC laser does, the average enhancement ratio (the output ratio between these two lasers) reaches $\sim 5.6\text{X}$, much higher than twice. That means the mirror reflective CLC laser has much higher efficiency, which is attributed to the double pump during the path of laser generation. In our experiment, the pump beam is around $\sim 200 \mu\text{m}$ in diameter. Hence for 10 μm cell gap, the pump beam can be almost completely reflected back to the original pumping area even at an oblique incidence.

Figures 5(a)-(b) depict the laser output power change along different analyzer directions at pump energy 30 $\mu\text{J}/\text{pulse}$ and 10 $\mu\text{J}/\text{pulse}$. The line with filled squares shows the experimental results and the line with filled circles shows the simulation results, calculated according to Malus's Law [9] as Eq.(1) shows:

$$I_{\text{output}} = \cos^2(\phi) \quad (1)$$

Here I_{output} is the output power after the analyzer and ϕ is the relative angle between the linearly polarized light and the analyzer. Results indicate that when rotating the analyzer before the detector, we observed the laser emission power changes according to the square of cosine at both low and high pump energies. When the original RCP laser light is reflected by the mirror coating, it is changed into LCP. This LCP will combine with RCP emitting from the other direction based on a coherent superposition with certain phase delay, leading to the linearly polarized output.

The exact linear polarization direction depends on the birefringence of the mixture and the thickness of the CLC layer [10].

To evaluate the purity of the linearly polarized light, we define the linearity β as:

$$\beta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (2)$$

where I_{\max} and I_{\min} represent the maximum and minimum light intensity when rotating the analyzer. A perfect linearly polarized light gives $\beta = 1$. Under this definition, our measured data show a linearity $\beta = 0.986$ at both high and low pumping regions, indicating a very pure linearly polarized laser light.

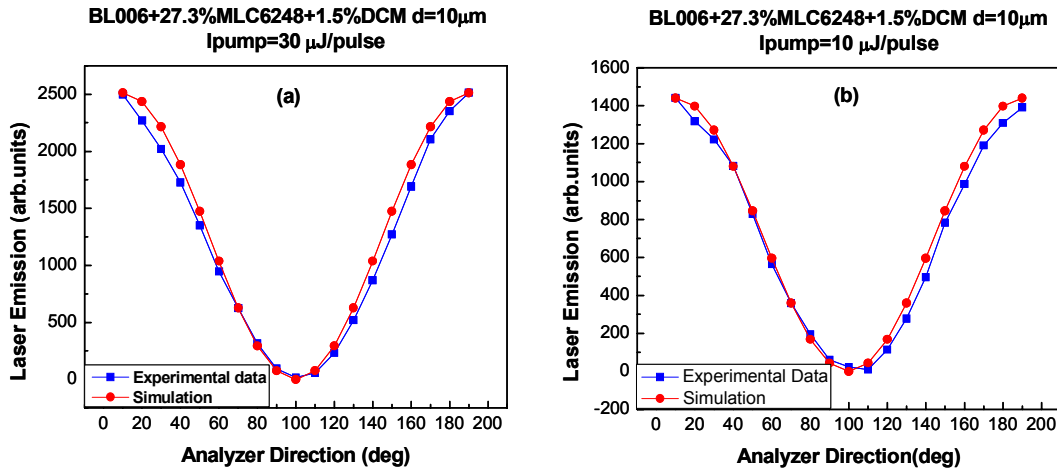


Fig. 5. Linearly polarized laser output change with the analyzer direction. (a): pump energy at 30 $\mu\text{J/pulse}$ and (b): pump energy at 10 $\mu\text{J/pulse}$.

Moreover, we demonstrated the spatial tuning of the linear polarization direction from this mirror-coated CLC laser. In order to fine tune the direction in a continuous manner, we made wedged cells with the cell gap varied around $\sim 8\text{-}15\ \mu\text{m}$. Because the cell gap increases gradually in a row within a wedged cell, the polarization direction can be controlled continuously at different spatial points. Two different wedged CLC lasers are made with slightly different cell gap variations. Then the CLC laser is scanning-pumped across the interference fringes. At different scanning positions, the linear polarization direction is found to rotate linearly with respect to the cell gap variation, as shown in Fig. 6 for wedged cells #1 and #2. The polarization angle is normalized to the starting point on the thinner side of the wedged cell. From both theory and experiment, the rotation period, which means the thickness variation over which the linearly polarized light will rotate 180° , can be obtained. According to the theory presented in Ref. 10, the rotation period can be expressed as:

$$P_{\text{calculated}} = \frac{2 \cdot \lambda_0}{\Delta n_{\text{eff}}}, \quad (3)$$

where Δn_{eff} and λ_0 are the birefringence of the whole CLC mixture and the lasing wavelength of the CLC laser.

Through experimental measurement, we can find the rotation period according to the total rotation angle and the corresponding cell gap variation for this angle since the cell gap varies linearly as Eq. (4) shows:

$$p_{measured} = \frac{d * 180^\circ}{\Delta\theta} \quad (4)$$

Where d and $\Delta\theta$ are the thickness variation and the rotation angle over the scanning range. Using the average refractive index of the CLC mixture $\Delta n_{eff}=1.67$ and lasing wavelength $\lambda_0=601$ nm, we found the calculated rotation period $P_{calculated}=5.8$ μm . In experiments, there are 32 fringes and 37 fringes, corresponding to 5.27 μm and 6.09 μm in wedged cell #1 and #2, respectively. The total rotation angle for the linear polarization is 164° and 188° . Therefore the measured rotation period $p_{measured}=5.78$ μm and $p_{measured}=5.83$ μm are found for wedged cell #1 and #2, respectively. This result agrees with the theoretically calculated results well; the error is within 1-2 fringes.

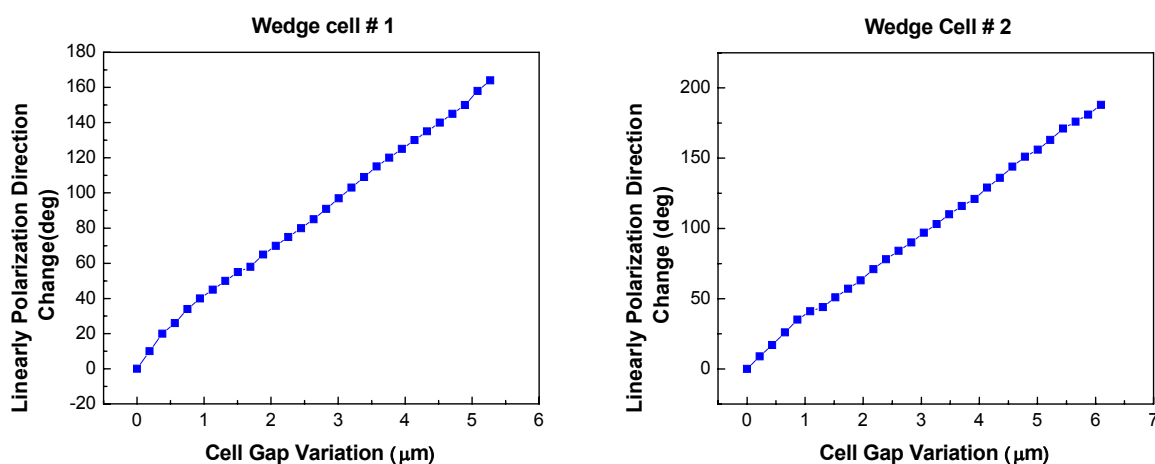


Fig. 6. Cell gap variation dependent linearly polarized light rotation for wedged cell #1(left) and wedge cell #2 (right).

3. CONCLUSIONS

We have demonstrated a nearly unpolarized laser emission from a CLC laser with metallic mirror attached to the outer surface of the glass substrate with the output doubled. The nearly unpolarized laser emission results from incoherent superposition of two orthogonal circularly polarized laser beams. On the other hand, we also demonstrated a linearly polarized laser emission with high linearity from CLC laser with metallic mirror coated on the inner side of the glass substrate. Emission can be enhanced by $\sim 5.6X$ due to the doubled pumping. The linearly polarized laser light originates from the coherent superposition of two orthogonal circularly polarized beams with certain phase delay between them. Furthermore, the spatial tuning of linear polarization direction is also demonstrated. This work is particularly useful for manipulating the polarization of the CLC lasers.

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