Electrically tunable lasers made from electro-optically active photonics band gap materials

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Abstract: External cavity-free and electrically tunable laser made from photonics band gap (PBG) materials with electrically tunable stop band is reported. The tunable PBG materials are developed from a family of novel cholesteric liquid crystals (CLC) with electrically variable pitch that adopts a non-constant distribution in space across the CLC film. The CLC exhibits a distributed feedback cavity whose resonant frequency can be electrically varied over a spectral range wider than 300 nm. Under an optical pumping and subject to a variable electric field, a tunable laser has been demonstrated in experiment that shows a wavelength tuning over 33 nm.

OCIS code: (140.3490) Lasers, distributed-feedback; (140.3600) Lasers, tunable; (160.3710) Liquid crystals; (250.2080) Electro-optic polymers.

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1. Introduction

Developing electrically tunable lasers featuring a wide wavelength tuning in a compact package without external cavity has long been pursued for vital applications in which the laser operation must be kept stable under severer environment impacts such as vibration, shocking, etc. One promising technology is based on photonics band gap (PBG) materials [1,2] preferably with tunable stop band. Significant efforts have been devoted to developing the lasers. For example, opals [3-5] PBG materials infiltrated with active liquid crystal together with fluorescent dyes have been suggested as a potential candidate. Second example is the thin-film organic semiconductor [the active medium is tris (8-hydroxyquinoline) aluminum (*Alq*) doped with the laser dye DCM] with different thickness of Alq:DCM [6] . However, no wavelength tuning has been realized from a device with fixed thickness based on these material systems. Classical cholesteric liquid crystal (CLC) represents another group of PBG material for lasing. Lasing from conventional CLC with constant pitch distribution has been reported [7-12]. But all the conventional CLCs are not variable in terms of spectral characteristics and no electrically tunable laser has been obtained even though mechanical tuning of the laser wavelength has been reported to a special elastomer material in cholesteric phase [13].

Recently, state-of-the-art electro-optically active CLC materials [14] have been developed, which exhibit an electrically variable stop band whose spectral characteristics such as spectral position and/or bandwidth can be varied over a spectral range wider than 300 nm in both visible and near infrared (IR) spectral regions. In this paper, we report for the first time on the electrically tunable laser developed from the electro-active CLC materials. A preliminary electrically tunable CLC laser has been demonstrated experimentally, which exhibits a spectral tuning over 33 nm [15].

2. Fundamentals

Laser based on cholesteric liquid crystal (CLC) material system was first reported by Kopp et al [8]. CLC is a self-organized periodic one-dimensional (1-D) structure, where the CLC molecular director rotates from plane to plane to form a periodic helical structure in either right- or left- handedness as shown in Fig. 1. The distance along the helical axis over which the director rotates 360^o is called pitch length P.

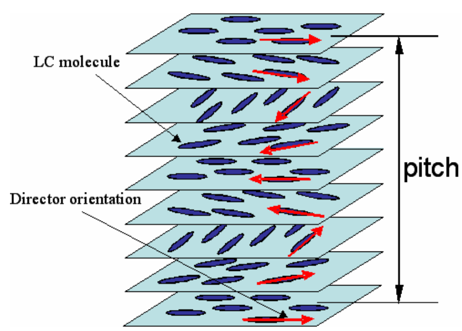

Fig. 1. Schematic of cholesteric LC

A conventional CLC exhibits a selective reflection band (or stop band) centered at λ_c due to its periodicity along the light propagation direction. With a *constant pitch,* conventional CLC central wavelength would not vary under an electric field. λ_c is defined by:

$$\lambda_c = n_a P \qquad (1)$$

where $n_a = (n_o + n_e)/2$ is the average of the ordinary and extraordinary refractive indices of the medium. The reflection bandwidth is determined by:

$$\Delta\lambda = \Delta n P \qquad (2)$$

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where $\Delta n = n_e - n_o$ is the CLC birefringence. For a sufficiently thick CLC, the reflectance of a normally incident light with a circular polarization matching to the CLC helical handedness approaches almost 100% within the stop band. However, the propagation of the light either with an opposite polarization or at the wavelength outside of the reflection band is unaffected and transmitted. Although a conventional CLC with a constant pitch can be switched between transparent and reflection states, its spectral characteristics such as the center wavelength as well as the bandwidth are not affected by the electric field.

Once a fluorescence material such as a laser dye is doped into a CLC, the emission spectrum of the fluorescent guest molecules is dramatically modified by the CLC helical structure: The fluorescence is suppressed inside the reflection band but significantly enhanced near the reflection band edges. This enhanced fluorescence leads to the lasing action much easier from a CLC with low pump threshold.

This CLC lasing mechanism has been theoretically explained by a classical model developed by Schmidtkea et al [16] that simulated the behavior of electromagnetic wave propagation within a CLC with a constant pitch. This model confirms the existence of the stop band of a CLC. It proves that within the stop band the electromagnetic field is evanescent, and the density of photon states (DOS) as well as the emission from a fluorescent material vanish. At the stop band edges the DOS as well as the emission are enhanced. Thus the model theoretically links the CLC lasing to the enhanced fluorescence, which is further linked to the enhanced DOS at the stop band edges.

It is then naturally predicted that if the spectral characteristics of the CLC stop band can be electrically altered, electrically tunable laser is created. Active CLC materials with electrically variable spectral characteristics have been developed from a series of liquid crystal composites in cholesteric phase [14]. Those CLC composites contain both low molecular weight chiral nematic and polymer network that is uniformly dispersed within the entire liquid crystal medium. Unlike conventional CLC, the pitch and/or the pitch distribution of these CLCs is variable in space, which is further alterable by an electric field. With the help from the polymer network, an electrically variable stop band whose bandwidth or center wavelength can be changed across a spectral band pass wider than 300 nm or so.

Lasing from the CLC with a spatially variable pitch [14] has been theoretically investigated [15] via a classical model similar to that developed by Schmidtkea et al [16] and the computer simulation results are shown in Fig. 2. For simplicity, the CLC is assumed to have a linear pitch distribution across the CLC thickness, which leads to a broadened stop band. Unlike conventional CLCs, the bandwidth of the variable pitch CLC is determined by

$$\Delta\lambda \approx n\Delta P \tag{3}$$

where $\Delta P = P_l - P_s$ is the difference between the longest pitch P_l and the shortest pitch P_s. The stop band bandwidth for the conventional and broadband CLC used in the simulations is 50nm and 100nm, respectively. Our simulation concludes that within the broadened stop band, both DOS and fluorescence emission are zero, similar to the CLC with a constant pitch. However, at the broadened stop band edges, both DOS and fluorescence emission are more significantly enhanced, as shown in Fig. 2, where a broadband CLC with a birefringence Δn = 0.1, a pitch number of 20, and a dye order parameter $S_d = 0.5$ are used. As compared to the conventional narrow band CLC with a constant pitch that is also shown in the figure, the broadband CLC exhibits a much more pronounced DOS enhancement at the stop band edges, which indicates an even lower lasing threshold. As shall be shown later, since the stop band spectral characteristics (i.e., the spectral position as well as the bandwidth) of such broadband CLC are electrically variable, an electrically tunable laser is becoming feasible.

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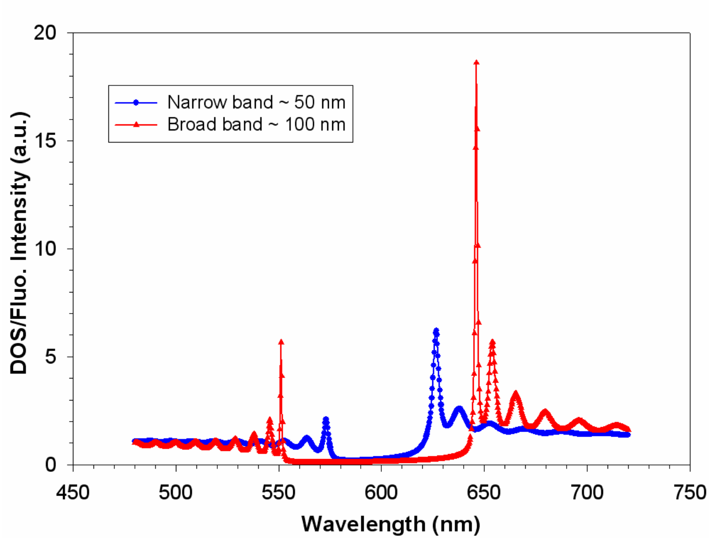

Fig. 2. Computer simulation of fluorescence/DOS from narrow and broad band CLCs

3. Experiment

In experiment, electrically variable CLC with a non-constant pitch distribution was prepared from a composite mixture containing cross-linkable monomer, low molecular weight (LMW) liquid crystal (LC), chiral additive, photo initiator, and laser dye of PM-597 and/or DCM. The dyed CLC film was sandwiched between two pieces of glass substrates with conductive Indium-Tin-Oxide (ITO) electrodes. The top and bottom glass substrates were coated with anti-parallel rubbed polyimide layer so that the CLC was stabilized in the planar texture where the helical axis was perpendicular to the glass substrates. The film was then photo-polymerized. After polymerization, a cross-linked polymer network was formed following the helical structure of the CLC. The prepared left-handed CLC film exhibits a broadened photonic stop band starting at 585nm and ending at 690nm with a total bandwidth (FWHM) around 105 nm when no voltage was applied as shown in Fig. 3.

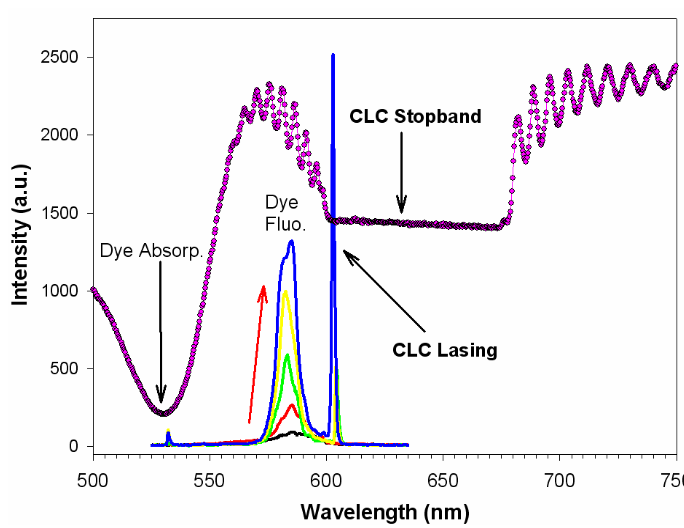

Fig. 3. Transmission of dyed broadband CLC and its lasing action under no E-field

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From the spectral measurements, the dye doped CLC exhibits a considerable absorption centered at around λ=532 nm region by the laser dye doped into the CLC. Therefore, a 532 nm pumping beam from a frequency-doubled Q-switched Nd: YAG laser (Tempest 10 from New Wave Research) was used as the pumping laser in the experiment. The pumping laser pulse duration is 4 ns with variable pulse energy and the pulse repetition rate is 10Hz. The pumping beam was focused by an f = 250 mm lens to have a slightly defocused beam spot size of around 50 μm in diameter on the CLC film. The broad fluorescence emission from the dye was observed between 575 and 595 nm, contributed from the dye PM-597. The lasing occurred at 601 nm with very narrow bandwidth of 1.5 nm. This lasing action was not observed if the pump laser power was lower than the threshold (refer to the red and black curves in Fig. 3). It is apparent that the lasing occurred at the CLC stop band edge of the short wavelength side. The corresponding CLC laser output as function of the pumping power has been measured, as shown in Fig. 4, where a lower lasing threshold was observed around 30 nJ/pulse. By fitting the experimental data using the classic relation of laser theory, a slope power of 1.90 was obtained against the pump laser power, which is very close to the theoretical value of 2, indicating a high quality CLC lasing. Also a round 21% efficiency has been achieved as seen in Fig. 4.

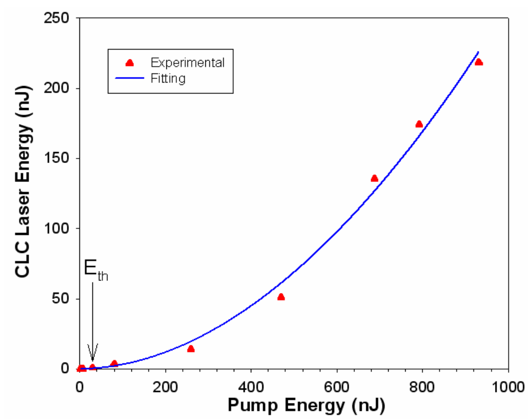

Fig. 4. CLC output power vs. pumping power

The output beam from CLC is always perpendicular to the CLC film surface, regardless of the pumping beam incident angle, which is attributed to the 1-D distributed feedback photonic structure. Under the longitudinal pumping configuration, where the incident angle of the pump beam was around 20^o–50^o with respect to the CLC film surface normal, the separation between the pumping and CLC lasing beams was simple and straightforward. Figure 5 shows the photo picture as well as the video clip of the tunable CLC lasing under the frequency-doubled Nd: YAG laser pumping, where the bright red spot is the laser beam generated from the CLC, which is spatially separated from the green pumping beam since the CLC is tilted with respect to the pumping beam. The large interference ring in red as seen in the picture originates from the laser beam interaction with the CLC helical structure, as suggested and proved by Kopp et al [9].

Therefore, the facts that the peak linewidth narrowing takes over the fluorescence when the pump laser power increases to above a well-defined threshold; the peak wavelength is located at the stop band edge; the directionality of the CLC output is always normal to the CLC film surface; and the interference ring pattern is generated from the interaction of the CLC output with the helical structure, comprise the typical characteristics of the lasing in the CLC photonic material system [7-9,11,12,14].

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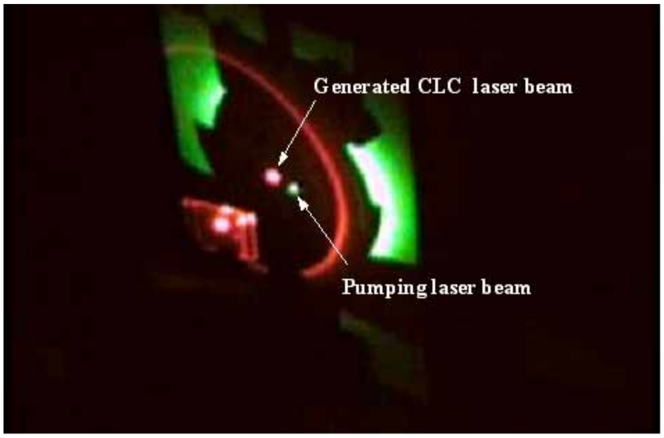

Fig. 5. Photo picture/video clip of tunable lasing from a CLC under 532 nm Nd:YAG pumping

Although lasing in the dyed CLC has been observed either at the shorter or longer side of the stop band edge or both sides simultaneously, currently the electric tuning of the CLC lasing is realized only in the system where the CLC lasing wavelength is at the longer side of the stop band. Such system has been fabricated with the liquid crystal composition modified. Under the variation of electric field across the CLC film, the stop band shifts correspondingly, which sequentially results in the lasing wavelength tuning. As shown by the series of 3-D curves in Fig. 6 where the narrow band laser peaks are superimposed onto the corresponding CLC reflection bands under different voltages, the laser wavelength experiences a blue-shift with the electric field increased. In the absence of an electric field, the CLC lasing wavelength is at 642 nm. As the applied voltage is increased, the CLC lasing wavelength gradually shifts to shorter wavelength. When the voltage is increased to 324 V, the lasing wavelength decreases to 609 nm, yielding a spectral tuning of 33 nm. The relationship of the CLC laser wavelength versus the applied voltage is plotted in Fig. 7.

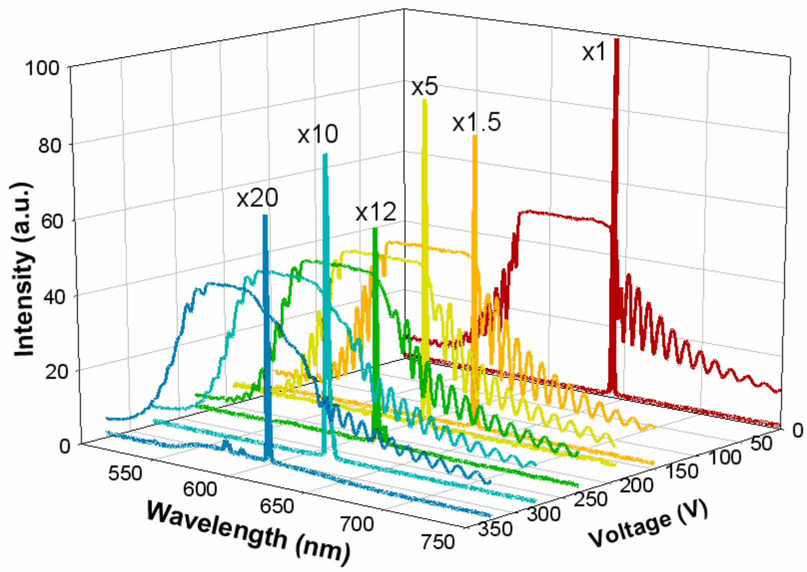

Fig. 6. Electrically tunable lasing from the tunable CLC

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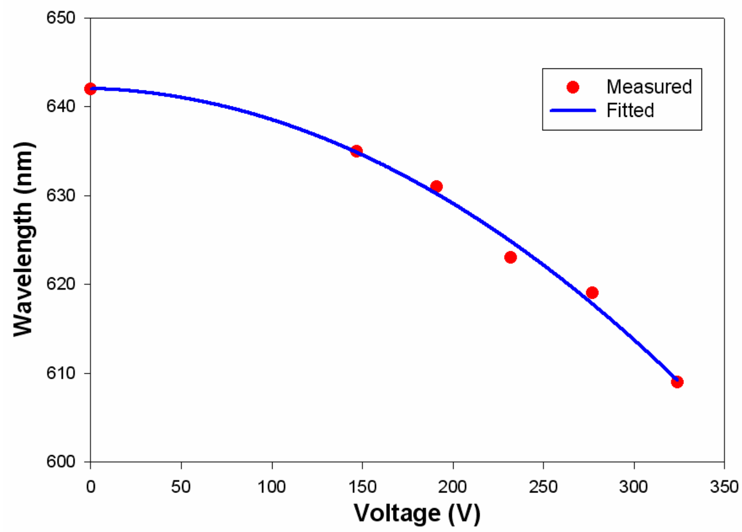

Fig. 7. CLC laser wavelength versus applied voltage

4. Conclusion

Tunable laser operation has been successfully demonstrated in experiment for the first time from an active CLC with a non-constant pitch distribution that is further variable via changing the electric field. Since this family of CLCs is essentially capable of providing a much broader tuning range, the future tunable laser should have a wider wavelength tuning than the currently achieved 33 nm if laser dye(s) with a wider fluorescence profile is used. Because no mechanical parts are involved in tuning the laser wavelength and no optical alignment is required, this tunable laser is stable and inherently insensitive to external vibration and shock. Since CLC has different textures, other configuration such as lateral pump edge-emitting may be expected. Also using high repetition rate (quasi-CW) pumping is under investigations.

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