Lasing at the edge of a photonic stop band in cholesteric liquid crystals

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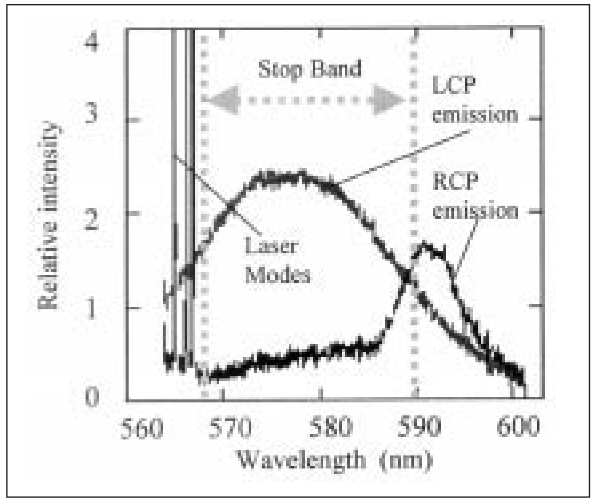
Modern electronics is based upon semiconductors, materials that possess a gap in the electronic energy spectrum as a result of coherent scattering in a periodic potential (Fig. 1). Light is emitted when electrons in the conduction band recombine with holes in the valence band. Because the excited electrons and holes are long lived their densities are readily controlled by an applied voltage.

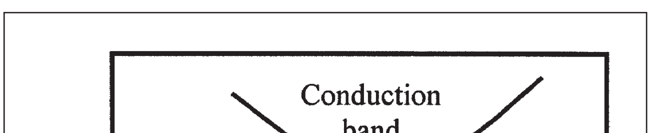
A decade ago Yablonovitch and John [1, 2] proposed that in certain dielectric structures with sufficiently large index contrast a photonic band gap (PBG) may exist in the spectrum of electromagnetic propagating waves, in analogy with the electronic band gap in semiconductors. Within the PBG, the electromagnetic field is evanescent and the density of photon states vanishes as the sample size grows. Since the rate of emission from an excited species is proportional to the density of photon states, emission within the band gap would be suppressed. Emission within the gap could occur however, if a defect state were introduced by disturbing the periodicity of the sample. Such a state would be localized with a spatial intensity profile that decays exponentially from the site of the defect. The dwell time of the localized photons would therefore be exponential in the sample's size leading to a correspondingly high intensity at the site of the localized state and to a narrow linewidth. Since this leads to enhanced stimulated emission into the defect mode while at the same time the inversion is not drained by emission into non-lasing modes, the threshold for lasing would be lowered.



▼ *Figure 2. Emission spectra from right handed sample for LCP and RCP emission. The height of the lasing lines is - 50 units.*

Lasing at defect modes in 3-D crystals has not as yet been reported, but recent progress on microfabrication promises that such lasers will soon become a reality. In contrast to defects within a 3-D band gap, we have considered a self- organized periodic 1-D structure — a dye-doped cholesteric liquid crystal (CLC). In this structure, the axes of the molecular director rotate from plane to plane to form a periodic helical structure with pitch P, which can be either right or left-handed. For films with thickness greater than 10μm, the reflectance of normally incident, circularly polarized light, with the same sign of rotation as the CLC structure, approaches 100% within a band centered at $\lambda_c = nP$, where $n = (n_o + n_e)/2$ is the average of the ordinary and extraordinary refractive indices of the medium. Light reflected within the structure has the same sign of rotation as the incident beam. The bandwidth is $\Delta\lambda \approx \lambda_c \Delta n/n$, $\Delta n = n_e - n_o$ [3, 4]. We find lasing at the edge of a reflection band from a right-handed structure (Fig. 1) for right circularly polarized (RCP) light propagating perpendicular to the molecular planes [5]. The propagation of left circularly polarized (LCP) light is unaffected by the structure and leads to a dye emission spectrum similar to that for molecules within a homogeneous host. Because the densities of states for LCP light in an RCP structure is a constant, the ratio of the emission of RCP and LCP light is proportional to the density of states of the RCP light. This ratio for the data in Fig. 1 shows a distinct gap within the reflection band and an enhancement at the band edge [5]. This reflects the pile up of states that have been expelled from the gap, which has also been observed in a layered dielectric medium [6].

Because the gap only exists within a limited range of directions, we expect that the lifetime of the molecular excited state is not appreciably modified by the periodic structure. However, the photon dwell time for states that participate in lasing is dramatically lengthened for the mode closest to the band edge and decreases rapidly for modes shifted further from the band edge. We find that the lasing threshold for a par-



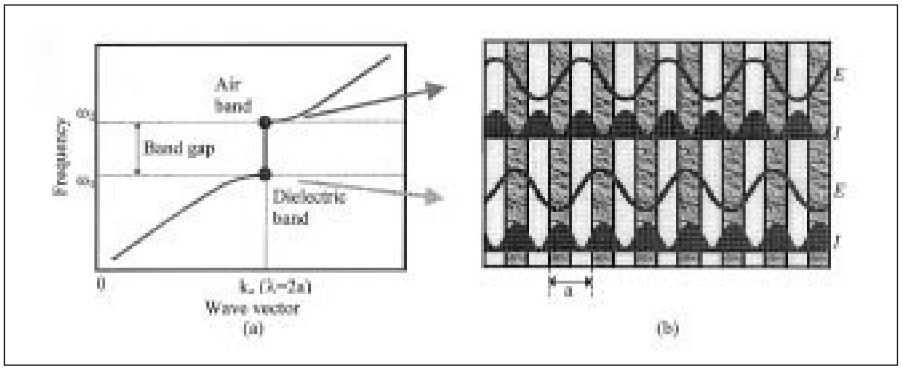
▼ *Figure 1. Energy-wave vector diagram for semiconductor.*

ticular mode increases with separation from the band edge. At the lowest powers, lasing occurs only for the mode closest to the band edge. The planar geometry of the 1-D structure conveniently leads to diffraction limited lasing within a narrow cone normal to the CLC planes.

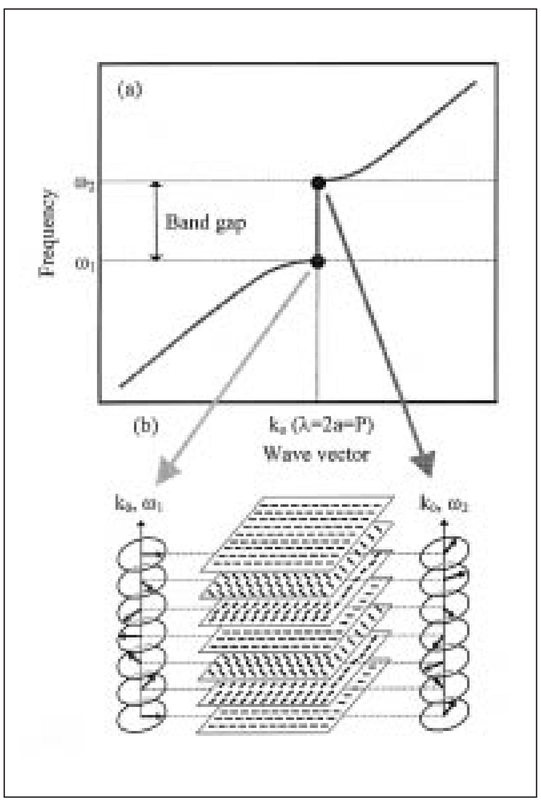
The character of the band structure of chiral systems is seen in simulations of wave propagation in these systems and is highlighted by a comparison with a layered dielectric system with alternating layers of equal thickness with indices of refraction equal to n_e and n_o. The anisotropic layers of the CLC have a thickness significantly less than the wavelength of light and successive layers have the direction of the molecular director rotated by the same small angle within the plane of the layer. Using the scattering matrix approach, we calculate the transmission and reflection from a single layer as well as the transmission and reflection from n+1 layers in terms of n layers. Thus, by induction, we are able to simulate wave propagation through a CLC sample of any thickness. Naturally, layered dielectric structures can also be simulated using this approach by replacing anisotropic with isotropic layers.

The simulation gives the transmittance and reflectance spectra of the CLC and layered dielectric structure as well as the distribution of the light intensity inside the medium. Within the reflection band for circularly polarized light with the same sign of rotation as the CLC, we find that the intensity falls exponentially and the light is a pure standing wave without a travelling wave component. This corresponds to a pure imaginary wave vector and the reflection band corresponds to a photonic stop band with a vanishing density of states for light of this polarization propagating perpendicular to the molecular planes.

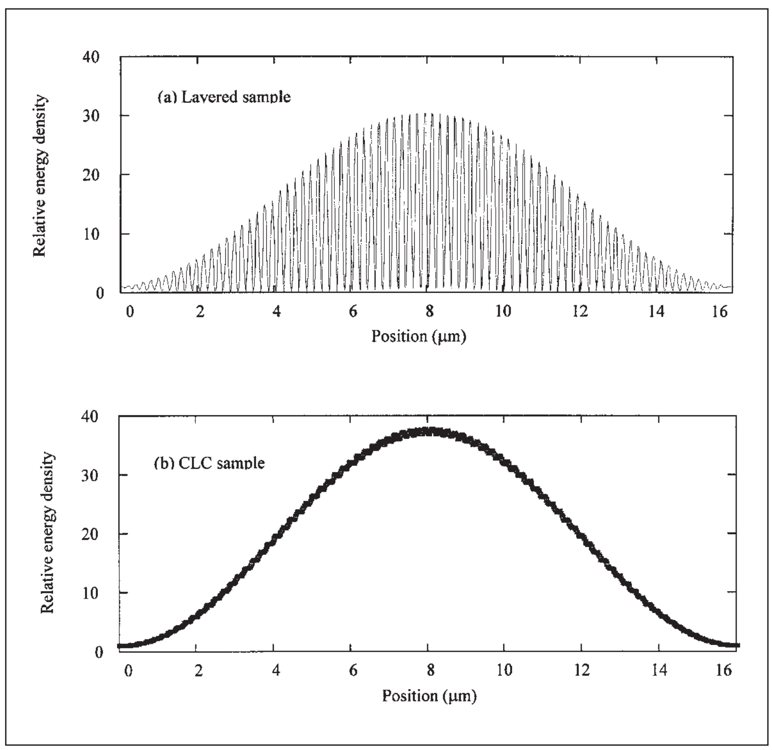
The simulations show significant differences between the properties of waves in CLCs and in layered dielectric media. Oscillations of the electromagnetic energy on the scale of a wavelength, which are found in layered dielectric media (Fig. 2) [7], are greatly suppressed in CLCs. Though the energy density is not rapidly modulated, the direction of the electric field of the standing circularly polarized wave, with the same sign of rotation as the CLC structure itself, rotates in space with pitch P. The electric field is always parallel (perpendicular) to the molecular director at the low (high) frequency edge of the stop band (Fig. 3). The results of the computer simulation of electromagnetic energy density within the sample for layered dielectric and CLC structures



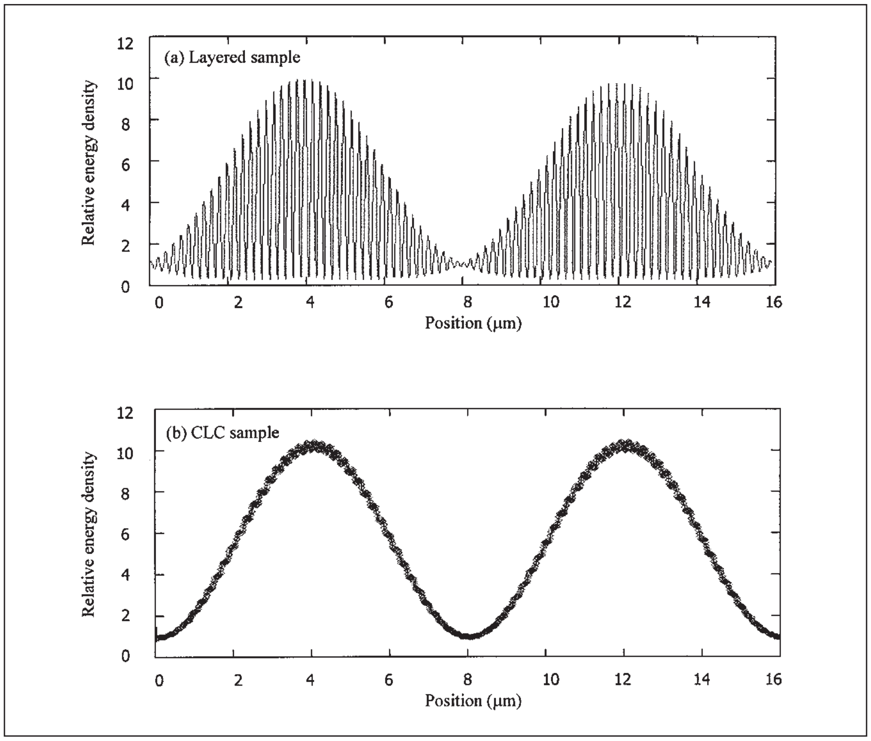
▼ *Figure 2. (a) Photonic band structure of a layered dielectric system with period a. (b) Dark and light layers correspond to high and low refractive indices, respectively. The electric field (E) and intensity (I) near the center of the sample are shown.*



▼ *Figure 3. (a) Photonic band structure of a CLC with a period a and pitch P-2a. (b) Arrows indicate the direction of the electric field near the center of the sample.*



▼ *Figure 4. Distribution of the energy density of the electromagnetic field inside a 1 -D periodic sample at the wavelength of the n = 1 mode. The refractive indices are 1.47 and 1.63 for the layers of the layered dielectric structure and for the ordinary and extraordinary indices of the CLC. The sample thickness is 16 μm and the period is 0.2 μm. The energy density of the incident wave is unity. (a) Layered media. (b) CLC - sample.*



▼ *Figure 5. Distribution of the energy density of the electromagnetic field inside a 1-D periodic sample at the wavelength of the n=2 mode. The parameters of the samples are the same as in fig. 4. (a) Layered media. (b) CLC-sample.*

with refractive indices of 1.47 and 1.63, period a = 0.2 μm, for the mode closest to the band edge for a sample with a total thickness of 16 μm are shown in Fig. 4. This difference between layered and CLC structures is also displayed for the second (Fig. 5) and higher order modes for which the intensity has a number of peaks inside the medium equal to the mode number n from the band edge. The slowly varying envelope corresponds to fields with Bloch wave vector $k = 2n\pi/L$. A comparison of the energy within the structure for n = 1 and 2 shows that for these strong resonances the energy is proportional to n^2 and the linewidth to $1/n^2$.

In conclusion, we observe lasing at the edge of a stop band in dye-doped CLC structures. The density of states is suppressed within the reflection band and enhanced at its edge. These results are consistent with simulations of optical propagation in CLC structures, which show a stop band with sharp structure in transmission and reflection near the band edge. The sharpness of these lines reflects the enhanced residence time for light at these frequencies. This is associated with significant enhancement of the density of states and of the intensity within the sample. We find that because the field in the CLC is polarized along or perpendicular to the molecular director, the width of the gap is greater in CLC materials than in layered dielectrics and the lines at the edge of the band are narrower for equal index differences. As a consequence of its band structure, efficient laser action is found at the wavelengths of the modes closest to the band edge. The ease with which these self-organized structures can be fabricated and their compact nature, suggests that these microlasers may find applications in integrated photonic devices and displays.

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