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HTML ABSTRACT + LINKS

Cholesteric liquid-crystal laser as an optic fiber-based temperature sensor

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In this work, we have studied the temperature dependence of a cholesteric liquid-crystal laser coupled to an optical fiber, with a view towards optical fiber sensor applications. To stabilize the laser emission, we developed a procedure to align the liquid crystal placed in the fiber. Unexpected oscillations in the laser emission were observed as the temperature was varied, which can be understood in terms of the competition between bulk and surface anchoring torques. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1781363]

Liquid crystals respond readily even to modest stimuli, and this makes their use possible in sensor as well as in display applications. The development of sensors made of optical fibers is attractive due to the implicit advantages of fibers, including low loss, small size, immunity to electromagnetic interference, and the possibility of large separation between the sensor and the reading station.

Cholesteric liquid crystals (CLCs) are a nematic liquid crystal composed of optically active molecules. As a consequence, the CLC structure acquires a spontaneous twist forming a periodic helix about an axis normal to the directions of preferred molecular orientation. In the helical structure, the director is perpendicular to the helix axis and its orientation varies linearly with its position along the helix axis. The periodic helical structure of CLCs results in a selective reflection band. In this band, incident light of the same handedness as the cholesteric structure is totally reflected.[1] The reflection band edges are at the free-space wavelengths $\lambda_{-}=n_e p$ and $\lambda_{+}=n_o p$, where n_e and n_o are the extraordinary and ordinary refractive indices, respectively, and p is the pitch of the helical structure.[2] If a fluorescent dye with an emission matching the reflection band is added to these materials, the fluorescence is suppressed in the reflection band, but is enhanced at the band edges, leading to mirrorless lasing. When an appropriately chosen CLC dye mixture is optically pumped, lasing can occur with extremely low threshold and high efficiency at the low-energy band edge.[3] The frequency of lasing depends on the material properties, and these properties have a strong sensitivity to external fields. This system may be used as a sensor, where the lasing frequency provides information about the external fields.

Laser devices have been demonstrated in numerous configurations, such as microrings, distributed feedback, and distributed Bragg reflectors.[4–6] Mirrorless lasing[7,8] was predicted and observed in one-dimensional cholesteric materials,[9,10] chiral ferroelectric smectic materials,[11] and polymeric CLCs.[12] Low-threshold distributed-feedback lasing was demonstrated in two-dimensional photonic crystals[5] and in the three-dimensional[13] cholesteric blue phase II. Lasing was demonstrated at various wavelengths in the visible, in dye-doped CLC, as well as in the UV, in pure CLC.[14]

Two different materials were used to study the temperature dependence of the response. Sample 1 was a mixture of 85 wt. % CLC BLO61 and 15 wt. % nematic LC E7. Sample 2 was prepared using 10 wt. % BL087 and 90 wt. % CLC BL088. Approximately 1.5 wt. % of DCM dye was dissolved in the liquid crystal mixtures, showing good solubility in the liquid.

The reflection band for the dye-doped CLC was measured using a planar cell with ITO-coated glass windows with a unidirectionally buffed polyimide alignment layer, providing strong anchoring along the rubbing direction. Mylar spacers were used to obtain a cell gap of 23 μm. To measure the reflection band, we used an Ocean Optics PC1000 fiber optic spectrometer.

To develop the device made of the CLC laser placed between fibers, we used a standard multimode fiber with 50-μm core diameter and 125-μm cladding diameter. The fiber ends were polished and treated to achieve the desired liquid-crystal orientation at the fiber–liquid crystal interface.

The process used to achieve the anchoring of CLC was coating of the fiber tip with a polyimide (PI2555) film. The treated fiber was positioned in the UltraTec bare fiber polisher and was rubbed in one direction only. This process showed to be effective in anchoring the CLC in the fiber and obtaining a stable laser emission. A second attempt was made by manually polishing the untreated fiber. This produced grooves in the surface of the fiber; however, this was not effective in obtaining a stable laser emission.

To construct the fiber–CLC–fiber device, the CLC dye mixture was injected into a Norland UVC Optical Splice connector and the treated fiber ends were inserted into each end of the connector. The CLC laser was then pumped at the other end of the fiber by the second harmonic ($\lambda=532$ nm) of a Q-switched Nd:YAG laser delivering 7-ns pulses. Two polarizers and a half-wave plate were placed in the optical path of the pump beam to control the pulse energy. This fiber–CLC–fiber device was placed on a hot stage unit to introduce variations of the temperature with a precision of ± 0.01 °C. With an optical microscope, it was possible to adjust the thickness of the CLC laser between the fibers to

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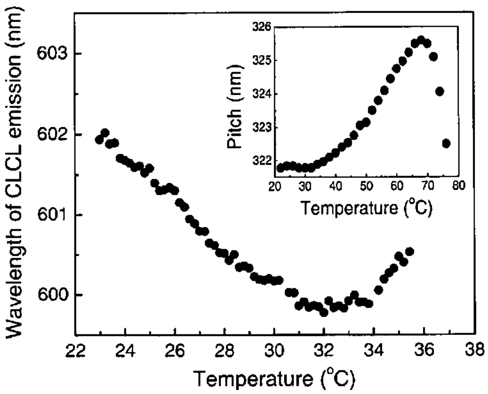

FIG. 1. Wavelength of CLC laser emission coupled to fiber vs temperature for sample 1. The inset presents pitch vs temperature.

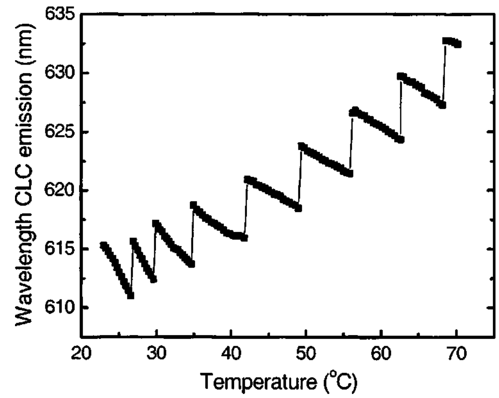

FIG. 3. Wavelength of CLC laser emission (sample 2) vs temperature.

approximately 20 μm. The output signal at the fiber end was monitored by a TRIAX 550 spectrometer.

At room temperature, the central wavelength of the reflection band of sample 1 is at 562.5 nm with a bandwidth of 74.8 nm, and the laser emission occurs in the low-energy band edge of the CLC at 603.4 nm with a bandwidth of 0.4 nm. The temperature dependence of the CLC laser emission is shown in Fig. 1. If the pitch was constant, the wavelength of the low-energy band edge should decrease with the temperature, together with the extraordinary refractive index. However, we observed an anomalous dependence of the laser emission wavelength with the temperature above 32 °C. In order to understand this behavior, we investigated the dependence of the pitch on temperature using the Cano wedge method.[15] In this method, a wedge-shaped cell was used, where the glass had been coated with ITO and polyimide to produce a homogenous alignment of the LC. A single mylar spacer was used at the thick edge of the wedge cell ($d = 23\ \mu$m). The pitch was determined by the relation, $p = 2d/n$, where n is the number of disclination line. The pitch temperature dependence is shown in the inset of Fig. 1 and its value at room temperature is 321.8 nm.

By analyzing the curves in Fig. 1, it can be seen that up to 32 °C the laser emission follows the same behavior as the refractive index, indicating a nearly constant pitch. For temperatures above 32 °C, the laser emission indicates that the pitch increases with temperature. As can be seen in Fig. 1, the cholesteric–isotropic phase transition occurs at 68 °C.

We also measured the wavelength at the edge of the reflection band for CLC without dye, as shown in the Fig. 2.

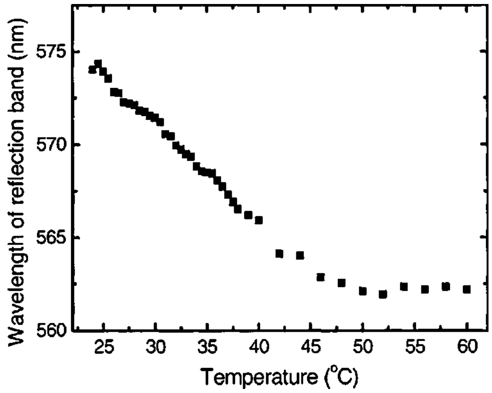

FIG. 2. Wavelength of the reflection band edge vs temperature for the undoped CLC (sample 1).

It can be seen that the wavelength decreases with the temperature in the same way as the refractive index, until 45 °C. The fact that the reflection band of undoped CLC monotonically decreases with temperature evidences the influence of the dye doping in the periodical structure of CLC. Above 45 °C we speculate that the combination of the variations of the pitch and of the refractive index with temperature results in the band edge being essentially constant.

In order to improve the response of the CLC laser emission wavelength with temperature, we tested a different LC in a planar cell (sample 2). As shown in Fig. 3, the lasing wavelength does not depend monotonically on temperature, but instead exhibits periodic discrete jumps between regions of smooth monotonic behavior. We believe these oscillations originate from the director, changing its orientation abruptly at the cell surfaces.[16,17] In essence, as the temperature is varied, the natural pitch (the pitch of an unbounded CLC sample) changes, and the number of half turns of the cholesteric helix, arising from the natural pitch, becomes incommensurate with the boundary conditions at the surface. Torques on the director from the bulk compete with those from surface anchoring, and if the anchoring is not infinitely strong, the equilibrium orientation of the director at the surface will vary with temperature. Since the anchoring potential is a periodic function of director orientation, at a critical bulk torque, the director loses stability and rapidly reorients to the new equilibrium position. The statics of this problem have already been discussed in the literature;[16,17] a quantitative description of the dynamics can be obtained by considering viscous, as well as elastic, contributions to bulk and surface torques. Computer simulations[18] of director dynamics have been recently carried out, showing satisfactory agreement with the experimental results. Preliminary results from experiments probing the dynamics indicate the presence of hysteresis as predicted by models for both the static and dynamic behavior.

We have demonstrated that it is possible to generate a stable laser emission in a CLC directly coupled to an optical fiber showing the viability of new optical fiber sensors. Lasing occurs at the low-energy band edge. The temperature dependence of the laser emission was considered in terms of the location of the band edge considering the effect of the refractive index and pitch. The temperature response of the CLC laser emission with temperature was investigated for two different sample materials. One sample exhibited a smooth but weak monotonic variation of the wavelength of laser emission with temperature, as expected from a sample where the natural pitch is nearly independent of temperature and the position of the reflection band edge is determined solely by the temperature variation of the extraordinary refractive index. A second sample exhibited a stronger temperature dependence, where the wavelength of the laser emission exhibited unexpected jumps. This behavior is consistent with an abrupt periodic reorientation of the director at the surface, corresponding to a half turn of the bulk helix between jumps. We attribute this behavior to competition between surface anchoring and bulk torques, originating in the temperature dependence of the pitch.

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