Polarized laser emission from an anisotropic one-dimensional photonic crystal laser

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The authors studied the laser emission from an anisotropic one-dimensional (1D) photonic crystal (PC) laser. An active medium layer, consisted of an epoxy resin doped with fluorescent dye, was sandwiched between two anisotropic 1D PC films. Efficient laser emissions were generated by optical pumping at relatively low lasing thresholds. The wavelengths of the emitted lasers were 611 and 618 nm, which correspond to the two split eigenmodes at the low-energy band edges due to the anisotropy of the PCs. The authors also demonstrated that the polarization of the lasing emission can be controlled by adjusting the birefringence of the PCs. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2723677]

Recently, intensive research has been conducted on photonic crystals (PCs) that have a periodic optical structure because of a photonic band gap (PBG) in which the existence of a certain energy range of photons is forbidden.[1,2] On the basis of physical concepts related to PBG predicted theoretically, various applications of PCs have been proposed for promising photonic devices.[3–9] Of these interesting applications, the study of a lasing at the PBG edge is a particularly attractive subject because the group velocity of the photon approaches zero and thus a low-threshold laser is expected.[9–15] Various trials have been conducted on low-threshold PC lasers, of which one of the simplest is a lasing from one-dimensional (1D) PC lasers. Although 1D PCs do not form complete three-dimensional PBGs, 1D photonic lasers are simple to make and hence potentially inexpensive; further, they have many applications. Thus, various studies on lasing with 1D PCs have been reported: photonic band-edge lasers,[9–12] and 1D PCs containing nematic liquid crystals (LCs).[13,14] More recently, to achieve high lasing efficiency with the wavelength tunability of the laser light, LCs that possess a large optical anisotropy were also introduced as an active medium layer in a 1D PC laser.[14,15] Despite the development of such efficient 1D PC lasers, it is necessary to improve their structure further because it is still difficult to control the polarization of lasing light in the device structures that have so far been proposed.

In this letter, we report on the development of a 1D PC laser that allows the polarization of lasing light to be controlled by using anisotropic 1D PCs. The anisotropic 1D photonic crystal laser presented an active medium layer sandwiched between two *anisotropic* 1D photonic crystal films, while the conventional 1D photonic band-edge laser[9–12] has an active medium layer sandwiched between two *isotropic* 1D photonic crystal films. It has been predicted that in anisotropic PCs, the photonic band structure would split with respect to the state of polarization of the interacting light, in contrast to the degenerated band structure of the typical isotropic PCs.[16–18]

The lasers were prepared by sandwiching a thin organic fluorescent active layer between two proper anisotropic 1D PC films as follows: an anisotropic 1D PC film/a dye-doped isotropic active layer/an anisotropic 1D PC film. For the anisotropic 1D PC film, a commercial 1D photonic band gap film (Magical film, Tokyu Hands Inc.) was used. The film was approximately 35 μm thick and the wavelength of middle of the selective reflection band was close to 600 nm. Further information about the structure of the film was unavailable. For the active medium layer for lasing, we prepared a transparent host epoxy resin doped with guest fluorescent dye, the fluorescent emission band wavelength of which was about 600 nm. The used dye was highly fluorescent 4-(dicyanomethylene)-2-*tert*-butyl-6(1,1,7,7-tetramethyljulolidyl-9-enyl)-4*H*-pyran (DCJTB), the fluorescence emission peak of which was about 635 nm. The full width at half maximum (FWHM) of the emission was about 78 nm. To mix DCJTB dye (1.5 wt %) and host epoxy homogenously, the DCJTB dye and the hardener and resin (1:1) of the epoxy were dissolved in a solvent of chloroform with a stirrer for an hour. After the solvent had dried completely, the homogeneous mixture of the dye-doped epoxy compounds was introduced between two PBG films, which were separated by spacers (2 μm) and subjected to uniform pressure to form an active layer of uniform thickness. Once the epoxy resin had hardened completely, optical transmittance spectra of the samples were measured by using a multichannel spectrometer (HR 4000CG-UV-NIR, Ocean Optics Inc., 0.25 nm resolution). For fluorescence and lasing experiments, a 355 nm pulsed laser beam from a third-harmonic light of neodymium doped yttrium aluminum garnet laser (Surelite III; Continuum) was used as an optical pumping source. A combination of a polarizer and an analyzer was also used to investigate the polarization of lasing light from the sample.

First, we observed the optical characteristics of the anisotropic and flexible PBG film. Figure 1(a) shows the polarized microphotograph of the film between crossed polarizers

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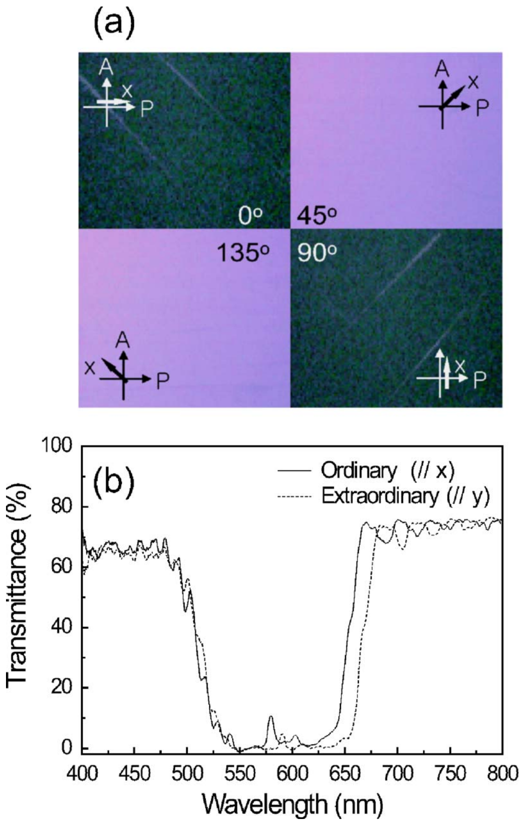

FIG. 1. (Color online) (a) Polarized photographs of the PBG film between crossed polarizers. (b) Polarized transmittance spectra for the incident lights polarized linearly along the *x* (ordinary) and *y* (extraordinary) axes.

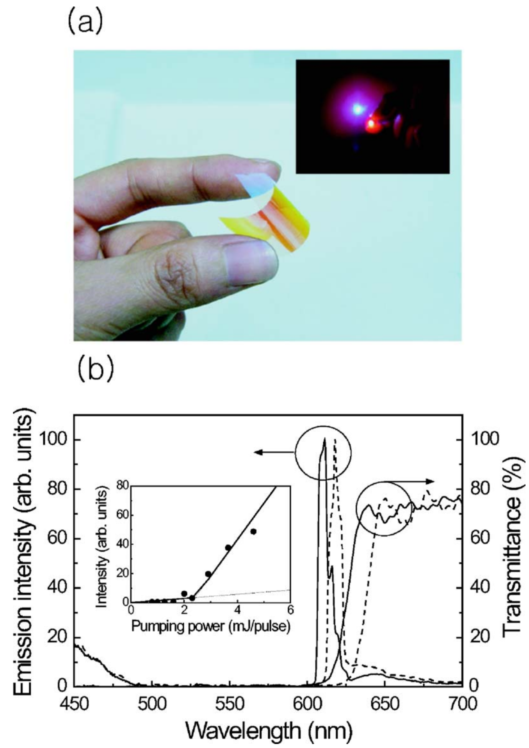

FIG. 2. (Color online) (a) Photograph of an anisotropic and flexible laser sample. Inset: lasing emission (red light) by optical pumping (blue light). (b) The lasing and the transmission spectra for the incident lights polarized linearly along the *o* (solid curves) and *e* (dashed curves) axes. Inset: threshold power behavior for *o* mode lasing.

at four angles of sample rotation. It is clear from the figure that the studied PBG film has optical birefringence. From the polarized microscope, we were able to define two optic axes, *x* and *y*, showing the darkest view. Then, polarized transmittance spectra from the PBG film were observed for the incident lights polarized linearly along *x* and *y* axes, as shown in Fig. 1(b). It is clear from the figure that the PBG bands and the width of the band depend strongly on the polarization of the incident light. The high-energy PBG edges are quite similar to each other for both incident lights polarized along *x* and *y*, while low-energy PBG edges are quite different from each other; there is a relatively narrow band gap for the incident lights polarized along the *x* axis, in contrast to a broad band gap for the incident lights polarized along the *y* axis. The difference between the band gaps indicates clearly that in the PBG film, the difference between the refractive indices of the alternative layers forming the 1D PC for a light polarized along the *y* direction is greater than that along the *x* direction. Thus, it is evident that the anisotropy induces the photonic band structure to split and that the *x* and *y* axes are ordinary (*o*) and extraordinary (*e*) axes, respectively.

Next, on the basis of the above information, we fabricated organic lasers as shown in Fig. 2(a). The active medium layer was sandwiched between the two anisotropic PBG films, whose *o* axes were parallel to each other. In order to see the lasing characteristics of the sample, we observed lasing spectra at normal incidence for both incident lights polarized linearly along the *o* and *e* axes. As shown in Fig. 2(b), the wavelength of the lasing peak depends strongly on the polarization of incident light. For the polarization of incident light along the *o* axis, the lasing emission occurs at the shorter low-energy band edge (*o*-mode lasing emission at 611 nm). By contrast, for the polarization of incident light along the *e* axis, the lasing emission occurs at the longer low-energy PBG edge (*e*-mode lasing emission at 618 nm). These lasing modes are caused by the high density of states (DOS) at the split band edges, in contrast to the degenerated photonic band edge in typical isotropic 1D photonic band-edge lasers. The highest DOS (not shown in the figure) at the band edge deduced from the PBG band spectra in Fig. 2(b) indicates clearly that the lasing operation is obtained at the two eigenmodes of the PBG. More details of the DOS will be reported elsewhere. The increased photon dwell time at the band edges allows amplification by stimulated emission for the given polarizations. The observed FWHM of the *o* or *e* mode emission was about 8 nm. The inset of Fig. 2(b) shows an example of a low lasing threshold of about 2.3 mJ/pulse for the *o* mode lasing peak.

Next, we observed the effect of the birefringence in the PBG film on the polarization of the laser light. Figure 3(a) shows the schematic optical setup used in the observation of polarized transmission and laser emission. Under laboratory coordinates (1, 2, 3), the incident light propagates along the 2 direction with a polarization parallel to the 1 direction. Note that, for the laser sample used in this observation, the *o* axis of the second PBG film was set at an angle (θ) of 45° with respect to the *o* axis of the first PBG film. The laser sample was mounted so that it lay in the surface normal direction coincident with the 2 direction and the *o* axis of the first PBG film is parallel to the 1 direction, as shown in the figure. After the laser sample, an analyzer was set and the rotation angle ϕ of the analyzer was defined as the angle between the 1 direction and the polarization axis of the analyzer. To in-

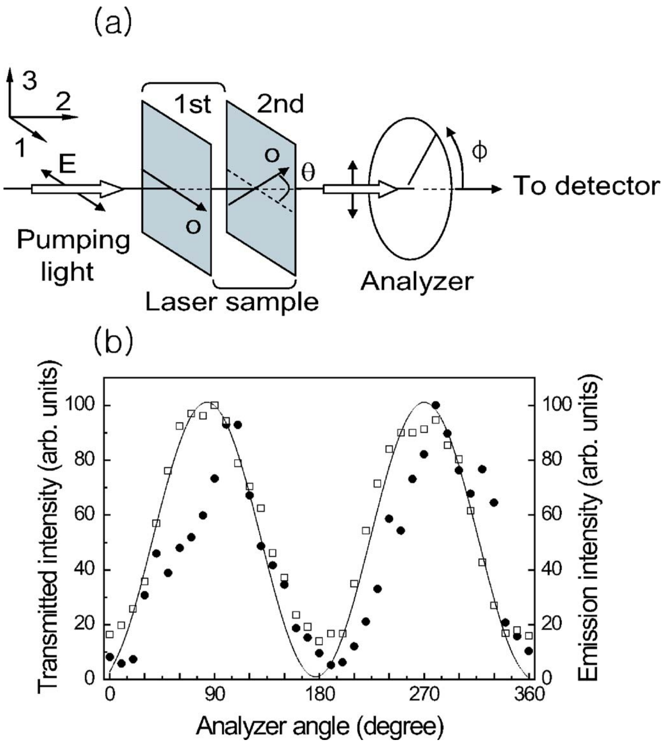

FIG. 3. Optical setup (a) for the polarization measurements. Transmitted (squares) and emission (circles) intensities as a function of the rotation angle ϕ of the analyzer. The calculated result is shown as a solid curve.

vestigate the birefringence of the laser sample, the transmission was measured for the linearly polarized incident light along the 1 direction with a wavelength of 633 nm. In Fig. 3(b), the squares show the transmitted intensity profile as a function of the analyzer angle of ϕ. In the figure, the transmitted intensity was nearly zero at $\phi=0°$ and 180°, while the transmitted intensity was at its maximum at $\phi=90°$ and 270°. This transmittance indicates that the polarization of incident light changes from the 1 direction to the 3 direction after passing through the laser sample. Upon consideration of $\theta=45°$ for the second PBG film, it will be evident that the PBG film of the laser acts as a $\lambda/2$ wave plate at a wavelength of 633 nm. For comparison, we calculated the transmitted intensity by using $\cos^2(\phi+\pi/2)$; the calculated result is shown in the figure as a solid curve. As may be seen from the figure, the experimental and calculated results agree well, which confirms the almost linear polarization along the 3 direction. Next, similar to the transmittance measurements, the lasing intensity from the sample was also measured as a function of the analyzer angle of ϕ and plotted in the figure as circles. The lasing intensity was also nearly zero at $\phi=0°$ and 180°, while it was at a maximum at $\phi=90°$ and 270°. These results are similar to those for the transmitted intensity. They mean that the lasing light is polarized almost linearly along the 3 direction for the pumping light polarized along the 1 direction due to the birefringence of $\lambda/2$ with $\theta=45°$ of the second PBG film. Note that these results cannot be obtained from the conventional isotropic 1D photonic band-edge laser. As shown in the figure, the experimental result also fits well with the calculated result of $\cos^2(\phi+\pi/2)$. Finally, note that when a laser sample with $\theta=0°$ was used, it was observed that the emitted laser light was polarized linearly along the 1 direction. Therefore, it is possible to control the birefringence of the PBG film and/or to change the angle between the axes of the anisotropic PBG films, in order to obtain different states of polarization for the lasing emission.

On the basis of the above results, an organic laser with a controlled polarization output can be fabricated easily by adjusting the birefringence of the PCs. The polarization output can be linear, circular, or elliptical, depending on the proposed application for the laser. Moreover, to realize electrical pumping for more practical applications, the laser structure suggested here can be combined with light-emitting devices such as organic light-emitting diodes (OLEDs). Then, one can also expect special light-emitting devices such as polarized microcavity OLEDs. Such devices can be used for polarized surface emitting lasers, displays, and/or polarized light sources of optical waveguide devices.

In conclusion, we fabricated an anisotropic organic laser with an active medium layer, consisted of epoxy resin doped with fluorescent dye. We demonstrated that efficient laser emissions were produced by optical pumping at relatively low lasing threshold. The wavelengths of the emitted laser lights correspond to the two split eigenmodes of the low-energy band edges. Moreover, we showed that the polarization of the emitted light can be controlled by altering the birefringence of the organic laser. Combining the device reported here with the optical devices reported elsewhere will surely lead to highly efficient polarized organic laser devices that will have a wide range of applications.

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