# Ultralow-threshold single-mode lasing based on a one-dimensional asymmetric photonic bandgap structure with liquid crystal as a defect layer

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In this Letter, we propose defect-mode lasing from a one-dimensional asymmetric photonic structure with dye-doped nematic liquid crystal as a central defect layer. The local field intensity of the distinguished single defect mode at the overlapped photonic band edges is drastically enhanced by the asymmetric structure consisting of two distinct multilayer photonic crystals. With high density of states of photons, effective output lasing emission and maximum input excitation are ensured. As a result, the single-mode lasing with a low excitation threshold of 0.2 μJ/pulse is achieved due to the combination of the defect layer and the photonic band edge effect. 

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Since John [1] and Yablonovitch [2] independently published their milestone papers on photonic crystals (PCs), the study of relevant topics has proceeded remarkably in the past two decades. One of the features of a PC is the periodic modulation of the dielectric constant giving rise to a photonic bandgap (PBG) that inhibits the propagation of light in a spectral region—the optical analog of the electronic bandgap in semiconductors. Using the physical concept related to PBGs, various applications of PCs have been reported, including microwave guides [3], optical filters [4], and three-dimensional omnidirectional reflectors [5]. With the insertion of a defect layer into a PC structure, defect modes can appear in the PBG, whose properties are governed by the optical thickness of the defect layer [6]. There are a number of ways of creating defect modes in the PBG. In particular, liquid crystal (LC) possessing field-tunable birefringence has attracted considerable attention for use as the defect layer in the PC structure. Based on various unique properties of LCs, a good number of tunable PC/LC hybrid devices have been proposed [7,8].

The first report on lasing from LC media dates back to 1976 [9]. Through the past decades, many researchers have observed coherent light emitting at the band edges of photonic LCs [10–13]. It is known that the group velocity tends to vanish at the band edges, leading to a high density of photon states (DOS) and, in turn, an enhanced gain factor. Hence, stimulated emission at the band edges or defect modes can be significantly enhanced. In this regard, researchers have engaged in fabrication of tunable LC laser devices either as distributed feedback lasers at the band edge frequencies or as defect-mode lasers at the localized defect-mode frequencies [14,15]. While the problem of band edge lasing in LCs, with possibilities of controlled lasing frequency, is discussed in detail in Ref. [16], the earliest studies and important achievements in the burgeoning area of LC lasers are well documented in Ref. [17].

Recently, defect-mode lasing based on a dye-containing defect layer introduced into a one-dimensional (1-D) periodic structure has been reported [18]. Unfortunately, the local intensity of the defect mode in such a symmetric PC structure was strongly suppressed and the PBG partially overlapped with the absorption band of the dye, resulting in a substantial reduction in intensity of fluorescence emission and, hence, increasing the lasing threshold. The defect modes induced by stacked cholesteric LC layers can lower the lasing threshold, but the process of fabrication is rather complicated [19]. In this Letter, we report on a 1-D *asymmetric* PC structure made of two dissimilar multilayer substrates sandwiching a dye-doped LC (DDLC) as a defect layer. According to Fermi's golden rule [20], the rate of emission at an angular frequency $\omega$ is proportional to the DOS, meaning that low-threshold lasing would occur with high DOS. To achieve the desired single-mode lasing with low-threshold excitation energy, we constructed the asymmetric PBG structure on the basis of the photonic band edge effect, as well as the addition of the DDLC defect layer. The resulting structure exhibited a strongly resonant mode and a high DOS at the overlapped photonic band edges of the constituent PCs, thus rendering itself as a potential device for ultralow-threshold laser and optical communication applications.

A schematic of the proposed PBG structure configured as [glass-$(H_1L_1)^4H_1$]-(DDLC)-[$(H_2L_2)^4H_2$-glass] is shown in Fig. 1. To create a noteworthy defect mode at a photonic band edge, we fabricated [glass-$(H_1L_1)^4H_1$] designated PC 1 and [$(H_2L_2)^4H_2$-glass] designated PC 2; i.e., two types of dielectric multilayers coated on glass substrates, allowing their corresponding PBGs to overlap around 560 nm. Figure 2(a) delineates the simulated normal-incidence transmission spectra of PC 1, PC 2, and the asymmetric 1-D assembly infiltrated with nematic LC as a defect layer. The simulation was carried out with a $4 \times 4$ Berreman matrix, and the parameters of the simulation were as follows: refractive indices of $n_e = 1.63$ and $n_o = 1.49$ (experimental conditions) [21], thickness of the LC layer = 3 μm, pretilt angle of LC = 3°, and the optical thicknesses of each dielectric layer for PC 1 and PC 2

 

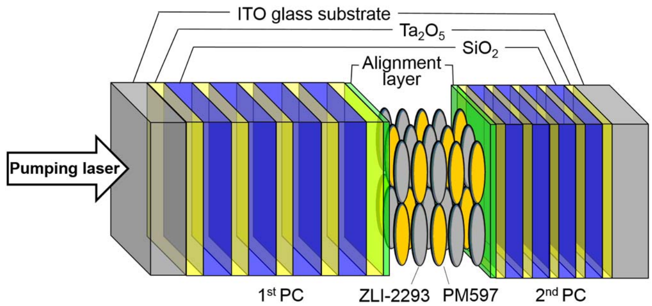


Fig. 1. 1-D asymmetric PBG structure with DDLC as a central defect layer. The substrate material is soda-lime glass.

as one-quarter of 660 and 480 nm, respectively. We designed the intersection of photonic band edges of the two PCs to be approximately 570 nm in order to match the excitation maximum of the laser dye. The polarization of the incident pumping light is parallel to the long axis of the LC (and, thus, the dye) molecules. From the simulation result [Fig. 2(a)], many defect modes exist in the two PBGs because of the nematic LC defect layer. The local intensity of the outstanding defect mode near the intersection of the two PBGs is remarkably enhanced. To further discuss the gain effect of the defect mode at the photonic band edges, we simulated the photon DOS $\rho(\omega) = dk/d\omega$ [22] distribution in the asymmetric structure comprising a LC defect layer in the middle [see also Fig. 2(a)]. The photon DOS is significantly enhanced at all defect-mode wavelengths,

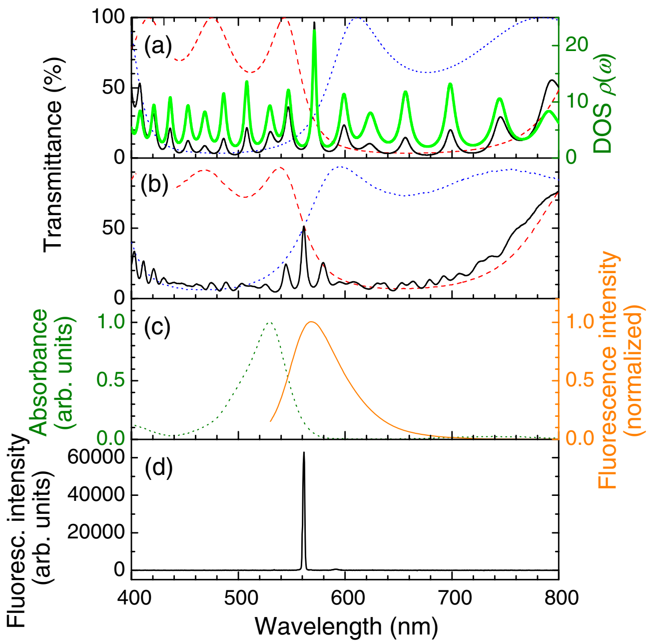


Fig. 2. (a) Simulated transmission spectra of PC 1 (red dashed line), PC 2 (blue dotted line), and the assembled structure sandwiching a nematic LC as central defect layer (black solid line). The corresponding density of states is represented by the thicker green solid line. (b) Measured transmission spectra of PC 1 (red dashed line), PC 2 (blue dotted line), and the 1-D asymmetric structure containing a DDLC defect layer (black solid line). (c) Absorption (olive dotted line) and fluorescence emission (orange solid line) spectra of 0.7 wt. % dye dispersed in LC. (d) Corresponding emission spectrum of the asymmetric structure containing a defect layer of DDLC.

particularly at the intersection of the two PBG edges, which means that the large photon DOS at the band edges is conducive to increasing the strength of the local intensity of the defect mode.

The high-refractive-index ($n_H = 2.18$) material, tantalum pentoxide ($Ta_2O_5$), and low-refractive-index ($n_L = 1.47$) material, silicon dioxide ($SiO_2$), were alternately deposited on indium–tin-oxide (ITO)-coated glass substrates using ion beam sputtering. As mentioned previously, the optical thickness of each dielectric layer of PC 1 (PC 2) is a quarter of 660 nm (480 nm). The polyimide SE-8793 (Nissan Chemical) was spin-coated atop the dielectric multilayer substrates, and the alignment layers formed were rubbed in antiparallel. The thickness of the DDLC is approximately 3 μm, as determined by ball spacers. The mixing ratio of the host nematic LC, ZLI-2293 (Merck) [21], to the laser dye dopant, Pyrromethene 597 (Exciton), is 99.3 : 0.7 wt.% for the DDLC defect layer. The transmission spectra of the first PC, the second PC, and the assembled hybrid structure containing DDLC in the middle was measured using a fiber-optic spectrometer (Ocean Optics, HR-2000+). Both the absorption and fluorescence spectra of the DDLC were acquired with an Acton SP2150 monochromator (Princeton Instruments). Laser light derived from a *Q*-switched Nd:YAG second harmonic generation pulse laser (Spectra Physics, Quanta-Ray Lab-130) was utilized as the pumping source for exciting the 1-D asymmetric PBG laser. The pulse-laser wavelength, pulse width, and repetition rate are 532 nm, 8 ns, and 10 Hz, respectively. The laser beam was focused on the 1-D asymmetric PBG structure to a spot diameter of 0.2 mm by a condensing lens, and the emission from the sample was detected with a fiber-based spectrometer (Ocean Optics, Jaz-Combo-2) with a resolution of 1 nm.

The experimental transmission spectra of the two dielectric mirrors PC 1 and PC 2 and the asymmetric PBG structure with DDLC as the defect layer are shown in Fig. 2(b). The percentage deviation in thickness of the sputtered films of PC 1 and PC 2 is less than 5%. The transmittance of the spectral peak associated with the distinctive defect mode at the intersection between the two PBGs is 51.4% at 561.4 nm (instead of at the designed wavelength near 570 nm) and the full width at half-maximum (FWHM) of the defect-mode peak is about 5.5 nm. Compared with the simulation result [see Fig. 2(a)], the transmittance of the defect mode at the overlapped band edges is not as high as in the experimental transmission spectrum. This can be explained by the fact that the overlapped wavelength region of the two PBGs is quite close to the absorption band of the dye dopant [Fig. 2(c), dotted curve]. Therefore, the defect-mode peak was somewhat suppressed due to the characteristic absorption of the dye.

To maximize the optical absorption by the dye dopant in hopes of lowering the lasing threshold, the pumping laser light was specifically polarized in the direction parallel to the long axis of the dye molecules aligned by the surrounding host LC molecules, whose orientation was dictated by those LC molecules near the alignment layers through the anchoring effect and the continuum phenomenon. Furthermore, the green laser pumping beam actually entered the 1-D asymmetric PBG structure from

PC 1 to prevent the pumping beam from being reflected by PC 2. Figure 2(d) depicts the emission spectrum of the asymmetric PBG structure consisting of a DDLC defect layer at 0.7 μJ/pulse pumping. The strong single-mode lasing was obtained at the expected wavelength of 561.4 nm of the distinctive defect mode with the highest DOS.

The central-wavelength emission intensity of the 1-D asymmetric PBG structure incorporated with a DDLC layer as a function of pumping energy is shown in Fig. 3. We observed a clear threshold behavior at about 0.2 μJ/pulse, beyond which the lasing emission intensity drastically increased. The corresponding threshold energy per excited area was calculated to be $\sim 0.6\ \mathrm{mJ \cdot cm^{-2}}$. The FWHM of the lasing peak dropped from 3.5 nm at the pumping energy of 0.1 μJ/pulse to less than 1.1 nm at 0.5 μJ/pulse pumping, which is a spectral limit of the experimental apparatus used. From this result, the laser action and single-mode lasing based on the proposed 1-D asymmetric PBG structure containing a DDLC layer were achieved. We note that the laser action with a lowered threshold stems from both the photonic band edge effect and the feature of a defect mode.

The defect-mode wavelength is determined by the optical length of the LC defect layer. Accordingly, one can shift the lasing wavelength by an applied voltage across the LC layer to change the effective refractive index in the LC bulk of a fixed physical thickness. In this work the wavelength tunability of lasing is much limited because the natural wavelength at 561.4 nm is within the tail of the dye absorption. This limitation can be resolved by using an alternative LC with higher optical anisotropy to allow a wider tunable range of the optical length. For example, lasing performance can be improved by substituting ZLI-2293 with E44. Our preliminary results indicate that the lasing peak can shift from its natural wavelength of 580 nm (at zero voltage) to 565 nm at 1.2 V. In this case, the measured pumping threshold for lasing is smaller than 0.1 μJ/pulse in that the lasing wavelength is well beyond the absorption band and yet still around the maximum of the dye emission band.

It is nontrivial to know how the extent of overlapping between the two PBGs affects the spectral characteristics of the defect mode of interest and, in turn, the lasing

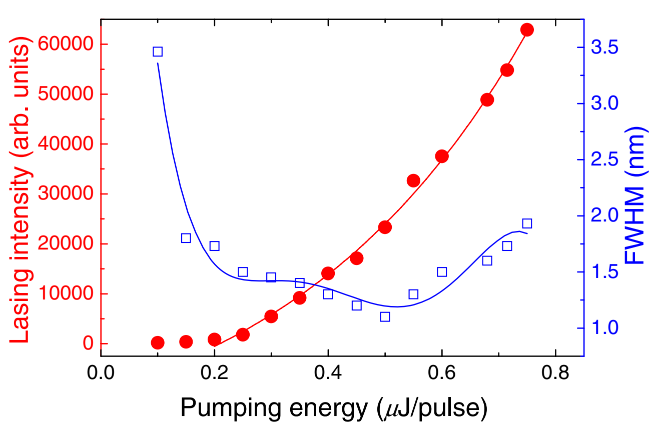


Fig. 3. Pumping energy dependence of the lasing emission and lasing linewidth (FWHM) for the 1-D PC 1–DDLC–PC 2 PBG structure.

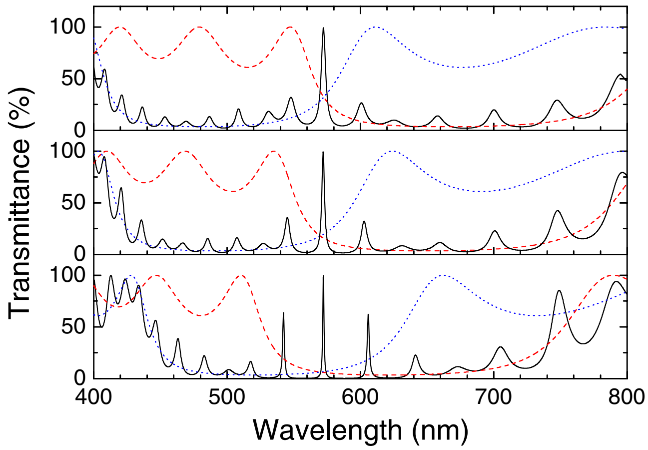


Fig. 4. Simulated spectral variations of an asymmetric PC 1–DDLC–PC 2 all caused by changing the central bandgap wavelengths of the two constituent PC substrates at (660, 480), (650, 490), and (630, 530) nm from the top to the bottom. The wavelength range of the PBG overlapping increases as the central wavelengths move toward each other, resulting in a sharper defect-mode peak at the band edge intersection.

quality. To further discuss the relation in the asymmetric 1-D PC 1–DDLC–PC 2 structure, three overlapping cases were considered. The transmittance spectra are given in Fig. 4. Here all simulation parameters are identical except that the central bandgap wavelengths of both PC 1 and PC 2 are varied so as to yield different overlapping conditions. One can see from Fig. 4 that the range of defect modes with significant transmittance widens with the extension of the overlapped PBG region. The FWHM of the central defect-mode peak decreases with increasing wavelength region of the overlapped PBGs (i.e., with decreasing transmittance at the intersection between the two PC band edges). The 1-D PC/DDLC structure having a broader overlapped PBG range is, thus, favored for lasing with higher coherence in addition to a possibly wider wavelength tunability.

In conclusion, single-mode lasing has been observed in an *asymmetric* PBG structure assembled with two distinct 1-D PCs sandwiching a DDLC defect layer. Such novel hybrid structure demonstrates the localization of photon field intensity in the resulting defect modes among which a distinctive high-transmittance defect-mode peak exists at the intersected wavelength between the two PBGs of the constituent PCs. By combining the properties of a dyed defect layer and the photonic band edges, the 1-D asymmetric PBG system unambiguously manifests itself as a promising device for ultralow-threshold laser and optical communication applications.

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