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Laser action from two-dimensional distributed feedback in photonic crystals

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We report an analysis of the operation of a new type of laser resonator with two-dimensional distributed feedback from a photonic crystal. The gain medium consists of a 2-(4-biphenylyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole host doped with Coumarin 490 and DCM and is deposited on lithographically patterned Si/SiO_2 structures. Bragg reflections caused by the grating diminish the group velocity of photons along some directions of crystallographic symmetry to zero, and the resulting feedback gives rise to laser oscillations. Dispersion relations for photons were calculated analytically and are used to interpret the laser emission spectra. © *1999 American Institute of Physics.* [S0003-6951(99)02001-X]

Organic gain media have been very useful in investigating the properties of several classes of laser resonators.[1–6] The principal reason for this is that, in many cases, it is relatively easy to fabricate lasers with solid-state organic gain media. Thus, organic and polymeric lasers have been used with advantage in pioneering studies of distributed feedback (DFB),[1] distributed Bragg reflector (DBR),[2] whispering-gallery mode,[3,4] and planar microcavity[5] lasers. We have sought to use solid-state organic gain media in the investigation of lasers based upon one- and two-dimensional photonic crystals and microcavities created from such structures. Berggren *et al.* have reported on the experimental characteristics of organic lasers based on planar resonators formed by a rhomboid lattice of shallow holes.[6] In this letter, we examine the lasing properties of resonators formed by a triangular lattice of shallow holes. We also calculate the dispersion relation for photons in such a structure and compare the measured lasing wavelengths with expected values based upon the calculations. The structures we employ in this study, while being two dimensional, do not possess a complete two-dimensional band gap.[7] The characteristics of lasers formed with such resonators are, however, important prerequisites for studying the characteristics of lasers formed with a complete two-dimensional band gap.

The structure of the lasers we examine in this letter is illustrated schematically in Fig. 1. A coating of photoresist on thermally oxidized silicon is patterned to form a triangular lattice of holes. The photolithography was performed with a 248 nm light source and involved advanced techniques to obtain feature sizes below the exposure wavelength. The periodicity of the pattern is 400 nm, and the typical radius of the holes is 100 nm. Shallow holes (of typical depth 20–40 nm) are etched in the SiO_2 by reactive ion etching through the photoresist mask. The holes are defined in the form of a triangular lattice [Fig. 1(b)] to facilitate analysis. The photoresist is then removed and a film of 2-(4-biphenylyl)-5-(4-tertbutylphenyl)-1,3,4-oxadiazole (PBD)

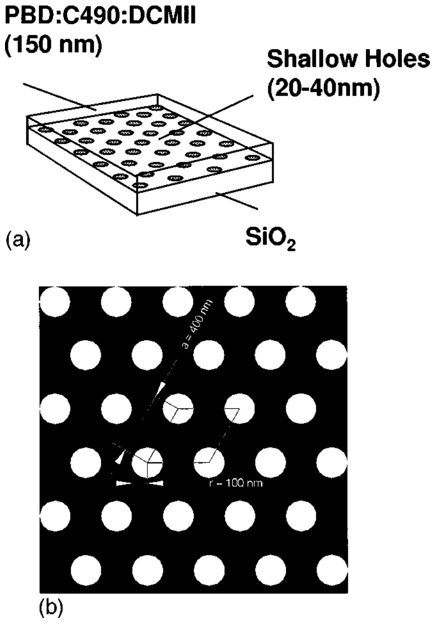

FIG. 1. (a) Schematic layer structure of the lasers employed in the study and (b) details of the two-dimensional triangular lattice.

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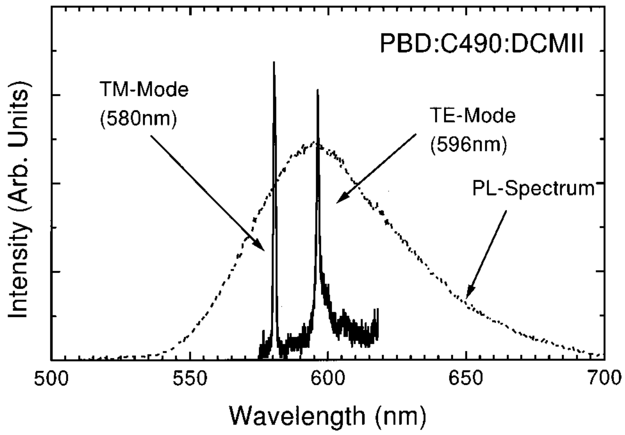

FIG. 2. Lasers emission spectra from the device shown in Fig. 1. The two peaks have different polarizations as shown. The spontaneous emission spectrum of the gain medium is also shown with a dashed line.

doped with about 1% by weight of coumarin 490 and DCM is deposited over the entire structure by spin coating. The thickness of this doped organic layer (150 nm) is such that the planar waveguide that is formed with the organic as the core layer and air and SiO_2 as the cladding layers supports only the lowest order transverse electric (TE) and transverse magnetic (TM) modes.

The structure described above was photoexcited with 337 nm light from a pulsed nitrogen laser (pulse width=2 ns) and the emission spectra measured with a charge coupled device (CCD) detector/spectrometer. The PBD molecules absorb the pump and funnel the excitation to DCM dye molecules through a process called cascade Förster transfer. The gain medium can be approximated by a four-level system.[8,9]

Above a threshold pump power of ~ 50 kW/cm^2, laser emission is observed in the wavelength range 580–600 nm and typical spectra are shown in Fig. 2. For convenience, the spectra are taken away from the plane of the waveguide (i.e., from the laser emission diffracted by the grating). The peak at 596 nm has a TE polarization, and the peak at 580 nm has a TM polarization. The threshold pump power for observing laser oscillation is significantly higher than the ~ 1 kW/cm^2 reported by us for third order DBR lasers with the same gain medium.[8] This is attributed to the lack of a complete gap, which results in a coupling between the lasing mode and other modes localized in the organic.

In order to attain a deeper understanding of the nature of laser action, we calculate the dispersion relations for the quasi-two-dimensional structure illustrated in Fig. 1 with the aid of a simple model. In the first approximation, the shallow holes are neglected and we consider a layer of gain medium on top of the unetched SiO_2 substrate. Let the thickness of the gain medium be d, and the dielectric constant of air, gain and substrate be ε_0, ε_1, and ε_2, respectively. We focus our attention on modes that are localized in the middle layer (evanescent both in air and in the substrate) and possess an in-plane wave vector of magnitude k. Matching boundary conditions at the interfaces yields a transcendental equation determining the dispersion relations $\omega(k)$ for the localized modes. The modes can be classified according to their polarization. For TE modes we obtain

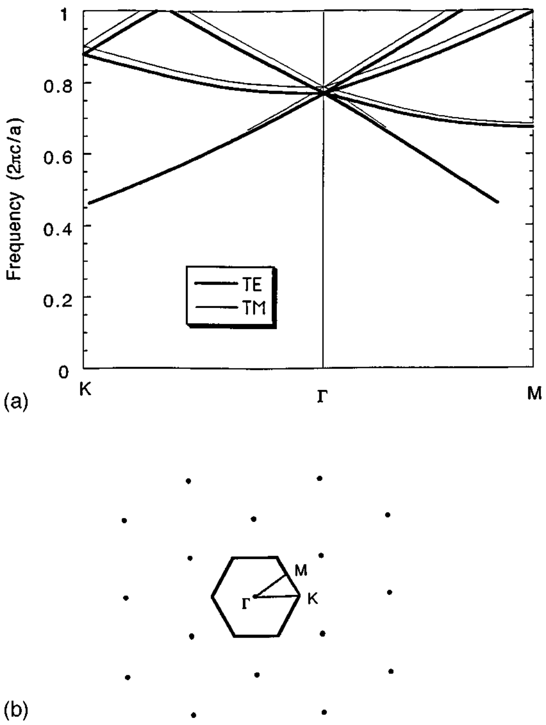

FIG. 3. (a) Calculated photonic band structure of the device shown in Fig.e 1 for TE and TM polarizations. For TE polarization, the electric field vector is in the plane of the waveguide. (b) The reciprocal lattice and the Brillouin zone showing the high-symmetry points.

$$\tan(d\sqrt{\varepsilon_1\omega^2-k^2})=\frac{\sqrt{\varepsilon_1\omega^2-k^2}(\sqrt{k^2-\varepsilon_0\omega^2}+\sqrt{k^2-\varepsilon_2\omega^2})}{\varepsilon_1\omega^2-k^2\sqrt{k^2-\varepsilon_0\omega^2}\sqrt{k^2-\varepsilon_2\omega^2}} \tag{1a}$$

and for TM modes:

$$\tan(d\sqrt{\varepsilon_1\omega^2-k^2}) = \frac{\varepsilon_1\sqrt{\varepsilon_1\omega^2k^2}(\varepsilon_2\sqrt{k^2-\varepsilon_0\omega^2}+\varepsilon_0\sqrt{k^2-\varepsilon_2\omega^2})}{\varepsilon_0\varepsilon_2(\varepsilon_1\omega^2-k^2)-\varepsilon_1^2\sqrt{k^2-\varepsilon_0\omega^2}\sqrt{k^2-\varepsilon_0\omega^2}}. \tag{1b}$$

These equations, which are similar to those used to solve for the modes in planar waveguides,[10] can be solved numerically. The first order modes have frequency cutoffs, below which no localized modes exist.

We treat the effect of shallow holes on this system as a perturbation. The two-dimensional grating imposes a periodicity on the system, so the bands may be represented in a reduced zone scheme. The resulting photonic band structure is shown in Fig. 3(a) for a triangular lattice with a lattice constant of $a=400$ nm, $d=140$ nm, $\varepsilon_0=1$ for air, $\varepsilon_1=1.7$ (Ref. 2) for the organic, and $\varepsilon_2=1.46$ (Ref. 2) for the substrate. The reciprocal lattice (which is also triangular) and the first Brillouin zone are shown in Fig. 3(b). The refractive index variation created by etching shallow holes opens up small band gaps at k points where bands of the same symmetry are degenerate. These gaps are not indicated in Fig. 3. As a result of coupling between bands, the group velocity of photons may become zero at high symmetry points in the Brillouin zone. At these wave vectors, standing waves form which provide ample feedback necessary for lasing action.

In order to identify the wave vector responsible for laser action in our structure, we look for degenerate bands at high symmetry points in the range of observed lasing wavelengths. This corresponds to the frequency range $\omega = 0.666 - 0.689\,2\pi c/a$, which selects the lowest two bands at the M point. Here both the TE and TM bands have zero gradient when holes are taken into account. We solve Eqs. (1a) and (1b) for this wave vector $(k = 2\pi/a)$ to obtain wavelengths 584 nm for the TM mode and 594 nm for the TE mode. These are almost exactly the wavelengths in Fig. 2 where laser action is observed. The small discrepancy is due to the uncertainty in measuring ε_1 and d as well as to the frequency shift caused by introducing the shallow holes. The latter effect is relatively small and is estimated to account for no more than a shift of 1–2 nanometers in the lasing wavelength observed.

The type of laser action described above is quite novel; furthermore, the basic device structure possesses the potential to be modified to allow for some very interesting technological possibilities. One such modification is the creation of a complete two-dimensional photonic band gap for at least one of the polarizations. Laser action from two-dimensional photonic crystals with a complete band gap has never been reported by any group. Organic gain media, in combination with advanced Si nanofabrication technology, should make this possible as suggested by our theoretical calculations. We will report on the results of such experiments elsewhere.

In summary, we have reported the characteristics of novel lasers with organic thin-film gain media. Laser action arises from two-dimensional distributed feedback from a triangular photonic crystal. The structures reported above do not possess a complete two-dimensional photonic band gap. However, the zero group velocity of photons along some directions of symmetry gives rise to laser oscillations. Dispersion relations for photons were calculated analytically and were used to interpret the laser emission spectra. The calculations predict two peaks of different polarizations at wavelengths in close agreement with experimental data. Our studies also indicate that such structures can be modified to possess a complete two-dimensional band gap.

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