Fabricating distributed feedback lasers from 2D photonic crystals

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New methods to increase control of photon-matter interactions in photonic crystals hold the key to revolutionizing the photovoltaic (PV) and display industries. Photonic crystals allow for the manipulation of light in ways that boost efficiency, especially for dye-sensitized solar cells and organic LEDs. They exhibit refractive index modulations at periodicities on the order of optical wavelengths, suppressing photon propagation much like electrons in a semiconductor lattice. Organic photonic crystals have inherently low index contrast, which allows for a moderate degree of structural irregularity as well as amenability to fabrication in large (>1cm²) lateral active areas.

One way to form all-organic photonic crystals is through holographic polymerization of liquid crystals (LCs), where interfering laser beams create periodically varying regions of high- and low-light intensity within a photopolymerizable resin.¹ In regions of high light intensity, rapid polymerization occurs, causing phase separation of LC droplets into low intensity regions. These holographic polymer-dispersed liquid crystals (H-PDLCs) enable one-step, rapid (<60sec) formation of multi-dimensional structures that exhibit the optical properties of photonic crystals and, with the LC component, allow electric field modulation of the refractive index.

Optically-pumped laser action of rhodamine 6G² and pyrromethene 597 (PM597)³ in H-PDLC one-dimensional reflection gratings resulted in reflections at the band gap edges to produce distributed feedback. In 2D H-PDLCs, no band gap forms because of the low index contrast (Δn < 0.20); however, light localization sufficient for laser action of incorporated dyes is achievable through the group velocity anomaly.⁴ This phenomenon is particular to 2D and 3D low index structures where the group velocity approaches zero as a result of mixing Bragg reflections induced by the periodicity of the lattice. Photons with energies within the group velocity anomaly, or flat band regions, form standing waves favorable for distributed feedback.

We fabricated 2D H-PDLC optically-pumped lasers predominantly consisting of a multi-functional polyacrylate (n = 1.52), TL213 LC (n̄ave = 1.64), and laser dye PM597.⁵ Interference of four laser beams resulted in a square lattice arrangement of LC columns within the polymer matrix with a lattice constant of 400nm, LC column diameter of ~80nm, and film thickness of 10 microns. Scanning electron microscopy (SEM) micrographs show 2D H-PDLCs along with a photograph of the actual cell (see Figure 1). Using a doubled 5ns Nd:YAG laser operating at 10Hz, we observed lasing from the PM597 at a threshold of 0.19mJ/cm² and a resolution limited linewidth of 1.9nm. Laser oscillation is clearly visible at around 600nm (see Figure 2).

Figure 1. SEM micrographs of 2D H-PDLC photonic crystals (top) and a comparison between the area of the hologram and a US dime.

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Figure 2. Photoluminescence (PL) from the PM597 H-PDLC, where laser oscillation is clearly visible at around 600nm.

Application of an electric field to the H-PDLCs aligns the nematic directors of the LC droplets in the field direction, which decreases the effective refractive index of the droplets and the index contrast of the structure from $\Delta n = 0.12$ to $\Delta n < 0.005$. With the decrease in index contrast, the eigenfrequencies of the photonic crystal increase. This manifests as a blue-shift in the laser mode and changes intensity with field strength (see Figure 3) where the lasing mode shifts from 594nm to 589nm and approaches the gain maximum of PM597, consequently increasing the lasing intensity. Further alignment of the nematic directors essentially erases the photonic crystal, leading to diminished coherent feedback.

The ability to observe lasing in photonic structures with no band gap demonstrates the importance of the group velocity anomaly for local field enhancement in multi-dimensional photonic crystals with low index contrast. Further studies in this area include the addition of electroluminescent dyes and reverse mode LC as a step toward electrically-pumped organic lasers.

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References