Photonic Crystals in a Polymer Laser

Thomas Boatwright[1], Yeheng Wu[1], James Andrews[2], Kenneth Singer[1], Joseph Lott[3], Hyunmin Song[3], Christoph Weder[3], Eric Baer[3]

[1]*Department of Physics, Case Western Reserve University*

[2]*Department of Physics & Astronomy, Youngstown State University*

[3]*Department of Macromolecular Science, Case Western Reserve University*

Center for Layered Polymeric Systems
http://clips.case.edu
NSF Science and Technology Center

Introduction

The combination of solid state physics and Maxwell's equations has resulted in the development of photonic crystals, which offer novel ways of manipulating a beam of light. The "crystals" consist of periodic arrays of materials with different indices of refraction. Solving Maxwell's equations for these structures reveals a region where light of certain frequencies cannot exist, a band gap, similar to the electronic band gap in semiconductor physics. This idea of a photonic analog to semiconductors was pioneered in the 1980s by Eli Yablonovitch and Sajeev John[1,2]. In addition, practical applications being investigated include LEDs, data storage, optical fibers[3], photonic integrated circuits and nanometer-scale lasers.

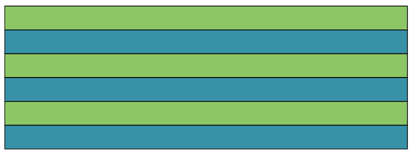


Figure 1 – A multilayer structure periodic in one direction, also known as a 1D photonic crystal. Typically, there are many more layers than the six shown.

Photonic crystals are suitable to laser applications since they behave like mirrors in the band gap frequency range[4]. Dowling *et al.*[5] showed that the optical path length near the band edge of the structure is greatly increased due to a decrease in the photon group velocity. When a gain medium is present, this effect allows for more gain and makes it more likely for lasing to occur. The gain threshold for lasing is given by:

$$g_t = -\frac{1}{2L}\ln\left(\frac{1}{r_1 r_2}\right)$$

where r_1 and r_2 are reflectivities of the mirrors (photonic crystals) and L is the length of the cavity between the mirrors[6].

Researchers have applied photonic crystals in what are known as vertical cavity surface emitting lasers (VCSELs). Devices similar to that shown in figure 2 have been constructed, mostly via spin coating polymers onto a substrate. In order to lase, the devices are pumped with a pulsed laser. Lasing thresholds for such devices have been measured to range from 12-50μJ/pulse.

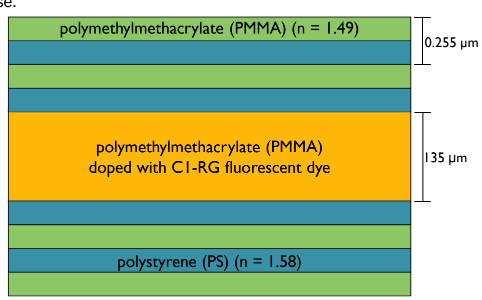


Figure 2 – A "defect" layer sandwiched by 2 photonic crystals with alternating layers of PMMA and PS. The thicknesses correspond to those in one of the samples tested.

Theory

By modeling the electric fields in the device shown in figure 2, one can calculate its transmission spectrum. The transmission spectrum illustrates the band gap, which is important in the laser application. The electric field in each layer has a form[7]:

$$E(x) = A_m e^{-ik_{mx}(x-x_m)} + B_m e^{ik_{mx}(x-x_m)}$$

where x_m is the layer boundary position and k_{mx} is the *x* component of the wave vector. The electric field in the slides holding the film is also accounted similarly. The relation between the initial and final coefficients can be represented in matrix form:

$$\begin{pmatrix} A_I \\ B_I \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_F \\ B_F \end{pmatrix}$$

It can then be shown that the reflectance and transmittance are:

$$R = \left|\frac{M_{21}}{M_{11}}\right|^2 \qquad T = \frac{n_F \cos\theta_F}{n_I \cos\theta_I}\left|M_{11}\right|^{-2}$$

Simulations

Through simulations, we determined how the defect layer thickness affects the band structure.

- Solved for 128 alternating layers of PMMA and PS in each photonic crystal
- Absorption of the dye not accounted for
- The calculations were done numerically so the curves are not continuous
- Assumed bilayer thickness was uniform and corresponded to band gap at 510nm

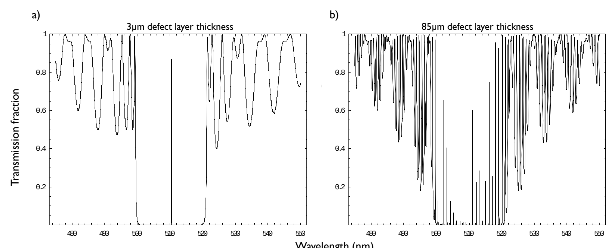


Figure 3 –
a) shows a 3μm defect layer with one major defect in the band gap.
b) shows more defects as the layer thickness is increased to 85μm

Materials and Methods

In order to experimentally test the validity of the simulations, the transmission of the samples was taken with a Cary Spectrophotometer. From its measurements, a plot similar to the ones in figure 3 was produced (see figure 5).

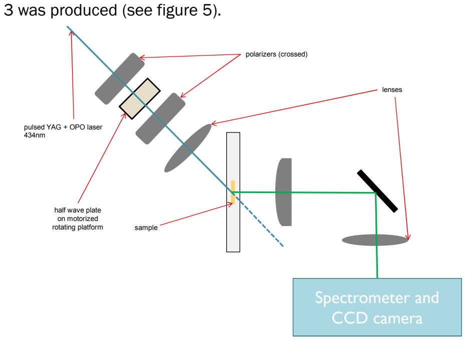


Figure 4 – To determine the lasing threshold of each sample, an experiment was needed to measure the emission spectra. The setup on the left shows how a pulsed YAG + OPO laser at 434nm pumps the multilayered sample. Another lens collects the sample emission. A detector then sends data of the spectrum to the computer. A similar setup was used to find the threshold. To finely tune the input intensity, a computer controlled motorized half wave plate between two polarizers which precisely attenuates the beam.

Results

Figure 5 – The transmission spectra of two samples with an 85 μm thick defect layer (red) and a 135 μm defect layer (black). The data was taken with a Cary UV-visible spectrophotometer at a 1nm spacing. The location of the band gap is very close to the target of 510nm. The low transmission at short wavelengths corresponds to the absorption characteristics of the dye.

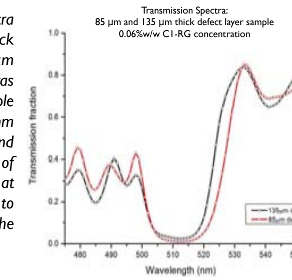


Figure 6 – The emission spectra of sample with a 85 μm thick defect layer and dye concentration of 0.06%w/w. It is shown that at the lasing transition, the spectrum becomes sharply peaked.

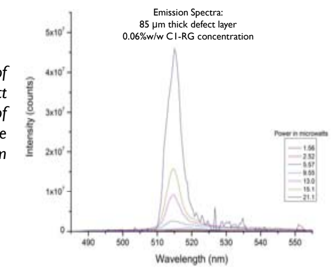
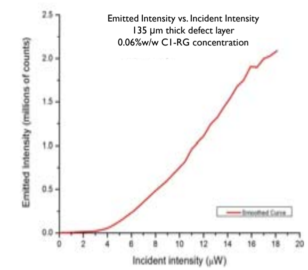


Figure 7 – A plot relating the power incident on the device to the emitted power for the 135 μm defect layer. The incident intensity was varied by utilizing a system of cross polarizers with a half wave plate between them to vary the attenuation. It is shown that around 4μW, a lasing transition occurs.



Acknowledgments

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