Photonics Crystals in a Laser

Thomas Boatwright1, Yeheng Wu2, James Andrews2, Kenneth Singer1, Joseph Lott3, Hyunmin Song3, Christoph Weder3, Eric Baer1

1Department of Physics, Case Western Reserve University
2Department of Physics & Astronomy, Youngstown State University
3Department of Macromolecular Science, Case Western Reserve University

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 John1,2. In addition, practical applications being investigated include LEDs, data storage, optical fibers3, photonic integrated circuits and nanometer-scale lasers.

Photonics crystals are suitable to laser applications since they behave like mirrors in the band gap frequency range1, Dowling et al.11 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:

$$g_{sh} = \frac{1}{\eta_r} \frac{n_2 \lambda_R}{c}$$

where $r_1$ and $r_2$ are reflectivities of the mirrors (photonic crystals) and $L$ is the length of the cavity between the mirrors5.

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.

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:

$$E(x) = A_n e^{ik_n(x-x_0)} + B_n e^{-ik_n(x-x_0)}$$

where $x_0$ is the layer boundary position and $k_n$ is the $n$ component of the wave vector. The electric field in the sliding holder is also accounted for. The relation between the initial and final coefficients can be represented in matrix form:

$$\begin{pmatrix} A_2 \\ M_1 \\ M_2 \\ A_1 \end{pmatrix} = \begin{pmatrix} A \\ B \\ M \\ M \end{pmatrix} \begin{pmatrix} A_1 \\ B_1 \\ M_1 \\ M_2 \end{pmatrix} \begin{pmatrix} A_2 \\ B_2 \\ M_2 \\ M_1 \end{pmatrix}$$

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

$$R = \frac{M_1}{M} \quad T = \frac{n_2 \cos \theta_2}{n_1 \cos \theta_1} |M|$$

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

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).

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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 a sample with an 85 µm thick defect layer. The emission transition power is given by $P_{em} = \frac{P_{inc}}{n}$, and $n$ is the number of layers.

Figure 7 – A plot relating the power incident on the device to the emitted power for the 135 µm defect layer. The incident intensity varied by using 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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References

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