18. Guiding Light Through Sharp Bends Using Two Dimensional Photonic Crystals

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The current effort to make integrated optical chips requires guiding light around sharp corners with a radius of curvature on the order of a wavelength. Light propagates in conventional waveguides as a result of total internal reflection at the interface between the high-refractive index guiding layer and its low-index surroundings. However, bends in the conventional index-contrast waveguides are susceptible to large optical losses depending on the radius of curvature of the bend. These optical losses due to radiation can be avoided by using a two-dimensional (2D) photonic crystal.

The 2D photonic crystal consists of an array of cylindrical rods of high dielectric material above a low dielectric material. Introducing a line defect, such as a row of smaller radius cylinders, into the 2D photonic crystal results in a linear waveguide. The forest of periodic dielectric rods surrounding the line defect creates a photonic band gap (PBG), i.e. a range of frequencies in which light cannot propagate. Thus, an optical signal with a frequency inside the PBG has its energy confined within the line defect and becomes evanescent into the photonic crystal. The radius of the cylinders in the line defect remains large enough to provide index guiding in the third dimension (normal to the plane of periodicity). The localization of a mode inside the line defect can be utilized to guide light around sharp corners including a 90° bend with low optical loss. This is illustrated in Figure 49.

Figure 49: (a) photonic crystal  (b) linear waveguide  (c) 90° bend waveguide
The cylindrical rods of the photonic crystal consist of a high-index, 860 nm epitaxial GaAs layer sandwiched between a 300 nm thick SiO₂ cap layer and a 640 nm thick low-index AlₓOᵧ layer. An additional 860 nm thick AlₓOᵧ layer is below the cylindrical rods in order to isolate the GaAs guiding layer from the GaAs substrate. The heterostructure is grown using gas source molecular beam epitaxy on a (100) GaAs substrate. The AlₓOᵧ is initially grown epitaxially as AlGaAs.

The fabrication process commences by sputtering 300 nm thick SiO₂ on the sample. Next, the waveguide and photonic crystal are defined using direct-write electron-beam lithography. Each sample is coated with polymethyl methacrylate (PMMA) electron beam resist, and each cylinder is defined by exposing a square pattern. The finite width of the beam rounds-off the corners of each square yielding a circular hole upon development. Simulation show that the largest band gap is obtained from a periodic arrangement of rods with diameter of 300 nm. To observe a shift in the frequency range of the PBG, patterns with cylinder diameters ranging from 270 nm to 330 nm are fabricated. Exposure-dose experiments are done to find the optimal parameters for the exposures. As shown in Figure 50, a dose of 375 µC/cm², current of 50 pA, and clock frequency of 0.09 MHz gave hole diameters close to the desired values. The input and output coupling waveguides and different sized arrays of holes are written by stitching together 250 µm fields.

![Figure 50. a) Top view SEM of e-beam-written patterns of photonic crystal in PMMA. The period is 500 nm and the diameter of the holes is 300 nm. The input and output waveguides are 1 µm wide. b) Side view SEM of a photonic crystal etched in GaAs using BCl₃ plasma. The GaAs is etched 2.44 µm deep.](image)

A 50 nm thick nickel film is evaporated on the sample after the PMMA is developed, and a liftoff process is performed. The pattern is transferred to the SiO₂ by reactive-ion etching (RIE) in a CHF₃ plasma after which the nickel mask is removed using nickel etchant. Using the SiO₂ mask, the cylindrical rods are created by etching the GaAs and the AlGaAs to a total depth of 1.5 µm in a BCl₃ plasma. Experiments were done using various metal masks as an alternative to the SiO₂ mask. However, the metal masks sputtered or degraded during the long duration of the GaAs/AlGaAs etch.

During the BCl₃ etch, the power and the DC bias are carefully monitored to control the etch rate and to avoid sputtering of the SiO₂ mask, hence eliminating micromasking. Also, the etching is done at low pressure and low flow to minimize the formation and excessive deposition of polymers on the mask and the waveguide sidewalls. As the etch gets deeper and the aspect ratio of the cylinders increases, lowering the BCl₃ flow minimizes microlaoding by making more radicals and ions available at the surface of the sample. This etching process leaves behind approximately 250 nm of the SiO₂ mask. Next, the AlGaAs is transformed into AlₓOᵧ using a wet thermal oxidation process. Finally, each substrate is lapped and the sample is cleaved in order to
create a smooth input facet to promote the efficient coupling of a test signal of 1.55 µm wavelength.

The fabrication of the 2D photonic crystal waveguide structures is near its completion. Different configurations of input and output coupling waveguides are currently under investigation in an effort to minimize coupling loss due to reflection at the edge of the photonic crystal. One case being tried is as shown in Figure 51. The input waveguide is inserted into the photonic crystal and tapered to a width of 300 nm. The output waveguide is inverse-tapered and it also starts inside the photonic crystal.

Figure 51. a) Top view SEM of e-beam written linear-defect with tapered input and output coupling waveguides in PMMA. b) Close-in SEM of e-beam written line-defect waveguide and tapered input and output waveguides in PMMA. The diameter of the defect holes is 250 nm and the diameter of the PBG holes is 300 nm. The tip of the tapered input waveguide is 330 nm wide, while the two tips of the output inverse-taper are both 228 nm wide. c) Side view SEM of same design after pattern transfer into GaAs using BCl₃ plasma. The GaAs was etched 2.43 µm deep.

In the near future, transmission through the various structures will be tested. Of particular interest is the size of the photonic bandgap and the transmission through a line defect waveguide. Coupling losses at the input and output of the 2D photonic crystal waveguide will be investigated. Finally, the transmission through a sharp 90° bend will be measured and compared to theoretical simulations.