Wavelength Demultiplexing by Beam Shifting Using a Dielectric Stack as a One-Dimensional Photonic Crystal

Bianca E. Nelson, Martina Gerken, David A. B. Miller, and Rafael Piestun
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

Chien-Chung Lin and James S. Harris, Jr.
Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4085

We show that a one-dimensional dielectric stack structure, shown schematically in Fig. 1, can be used as a wavelength demultiplexer with angular dispersion many times higher than that of a conventional grating or prism. This 30-period device is based on the "superprism" effect in photonic crystals. Previously, Zengerle [1] demonstrated this effect in singly and doubly periodic planar waveguides, while Kosaka et al [2] used a three-dimensional photonic crystal structure. While these devices are relatively complicated to fabricate, our structure is can be fabricated using readily available techniques, and in contrast to conventional prisms and gratings, our device is relatively compact. We experimentally demonstrate the spatial separation of two beams with a 4-nm wavelength difference by a distance greater than their beam width.

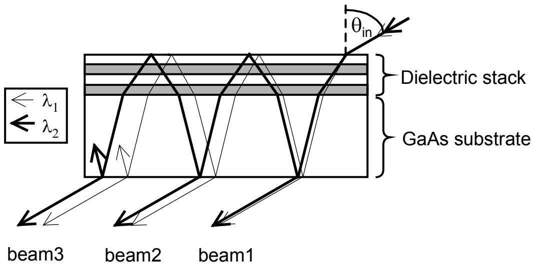

Fig. 1. Schematic of device. For clarity, the figure is not to scale, and only two periods of layer pairs are indicated. The beam paths of two different wavelengths are shown, including exiting beams due to multiple bounces within the structure.

Dielectric stacks are commonly used as mirrors. Here, however, we deliberately operate at wavelengths just outside the main reflection band, where there is strong group velocity dispersion and waves may still propagate through the structure. For a beam incident at an angle, the group velocity dispersion gives rise to a wavelength-dependent shift of the beam, since it is the group velocity, and not the phase velocity, that governs the direction of propagation of a light beam [3]. Such a structure has a range of incident angles and wavelengths for which the Bloch wavevector, K, is not real. These ranges correspond to total reflection, or equivalently, a one-dimensional photonic band gap. Near this band edge the propagation angle in the structure changes rapidly with change in wavelength. We can exploit this property to get a large beam-steering effect in the structure. For wavelengths 5 nm or less away from the photonic band edge, we calculate the angular dispersion, $d\theta_g/d\lambda$, to be greater than 2 degrees per nm. Within 1 nm of the band edge, the angular dispersion is calculated to be greater than 10 degrees per nm, and in fact approaches infinity at the band edge. Note that a full photonic band gap—that is, a band gap for all angles of incidence—is not necessary in this device.

The structure used in this experiment is a 30-period stack of alternating 80 nm thick layers of GaAs ($n \cong 3.6$) and AlGaAs ($n \cong 3.0$), grown on a 500 μm thick GaAs substrate by molecular beam epitaxy. Because air and GaAs are both essentially isotropic materials, all angular separation of wavelengths due to group velocity dispersion takes place in the dielectric stack. Once in air or GaAs, these angles are translated to lateral displacements of the beams. Both the dielectric stack and the GaAs-air interface of the substrate act as mirrors (albeit poor ones) and so several parallel beams can be seen to exit the sample, each a result of successive bounces between these mirrors. Hence we simplify fabrication by making a relatively thin dielectric stack structure, and yet we can observe the increased wavelength separation of a thick structure by using a multiple-bounce beam.

A microscope objective was used to focus a beam of TE-polarized light from a tunable continuous wave Ti:Sapphire laser onto the sample, which was cleaved from near the edge of the wafer. The $1/e^2$ gaussian beam diameter of the focussed spot was approximately 10 μm. As the wavelength of the laser was varied, this transmitted light was then measured with a photodetector to record transmission as a function of wavelength. This allowed us to verify the location of the reflection edge, and to determine the wavelength range of interest. To measure the shift of the beam with wavelength, the transmitted light was imaged onto a CCD camera and displayed on a video monitor. The signal from the monitor was also analyzed with a digital oscilloscope, so that it could then be recorded and measured. Over a range of 10 nm near the photonic band edge, the position of the beam can be seen to shift by approximately 4 μm, as shown in Fig. 2. Simulations performed with a full transfer matrix approach [3] show that these beam-steering effects take place even for just a few periods and that 30 periods can be considered approximately "infinite".

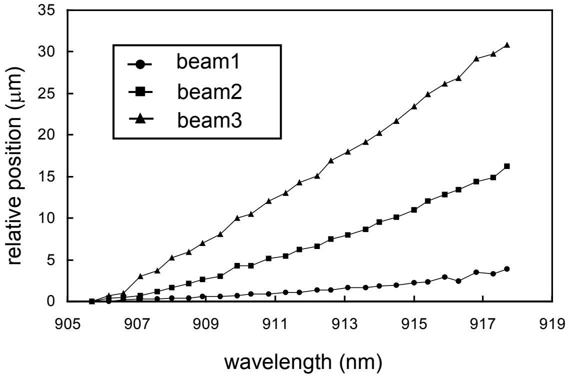

Fig. 2. Relative beam position vs. wavelength near the band edge for beams with increasing number of reflections within the structure.

In addition to the shift of this primary beam, the shifts of the next two multiple-bounce beams, “beam2” and “beam3”, are also shown in Fig. 2 to demonstrate the increase in shift for an equivalently thicker structure. The third beam shifted by over 30 μm for the same 10 nm wavelength range. Fig. 3 shows the intensity profile of this third beam, which can be closely modeled as having a gaussian beam shape, at two different wavelengths near the reflection edge. With a wavelength difference of 4 nm, the two beams are separated by approximately 12 μm, greater than the gaussian beam width of either beam. This resolution is a necessary performance requirement if such a structure is to be considered as a wavelength-separating device for WDM. The small fringes seen near the peaks are due to interference from neighboring multiple-bounce beams. Additionally, the beam suffers some width broadening as its wavelength gets very close to the band edge because of the group velocity dispersion in the structure. While the fringes are an artifact of the experimental set-up and could be eliminated, the effect of beam broadening is an inherent property of the structure and could be a limiting factor when using such a device for wavelength separation. The two spatially separated beams in Fig. 3, however, are far enough from the reflection edge as to have had little to no broadening.

In conclusion, we have demonstrated wavelength separation using a dielectric stack, and suggest that this fundamental property of one-dimensional photonic crystals can be exploited to create a compact, highly dispersive device for WDM. In contrast to previously suggested devices, this one-dimensional structure is simple and inexpensive to fabricate and is made from readily available materials. Additionally, because of the inherent scalability of photonic crystal properties, such a device could be designed for use at any wavelength of interest. We note also that it is not essential that the device be periodic. Many other layered structures with substantial group velocity dispersion would appear to be possible.

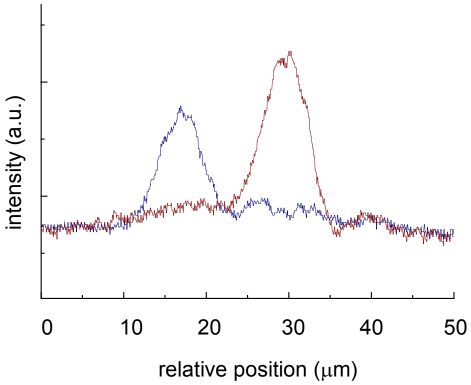

Fig. 3. Overlapped oscilloscope traces from the CCD line scan (intensity vs. position) of two resolved beams. The left beam is at a wavelength of 909.2 nm, and the right beam is at 913.2 nm. The physical separation of the two beams is 12.3 μm, and the two gaussian beam widths are 10.4 μm and 10.9 μm.

This work was supported by a grant number F49620-97-1-0517 of the Air Force Office of Scientific Research and DARPA. Martina Gerken also acknowledges the support of the Sequoia Capital Stanford Graduate Fellowship.

References

1. R. Zengerle, J. Mod. Opt. **34**, 1589 (1987).
2. H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, Appl. Phys. Lett. **74**, 1370 (1999).
3. P. Yeh, A. Yariv, and C. Hong, J. Opt. Soc. Am. **67**, 423 (1977).