

# Use of a dielectric stack as a one-dimensional photonic crystal for wavelength demultiplexing by beam shifting

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We demonstrate the use of a 30-period dielectric stack structure as a highly dispersive device to spatially separate two beams with a 4-nm wavelength difference by more than their beam width. Unlike previous devices, our structure is simple to fabricate and relatively compact. We discuss possible applications of our device within wavelength-division multiplexing systems. © 2000 Optical Society of America

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In long-distance telecommunications, wavelength-division multiplexing (WDM) has become a standard technique for handling the ever-increasing amounts of data traffic. As bandwidth needs increase for metropolitan- and local-area networks, the use of WDM for shorter distances becomes a necessary step. Many WDM devices in current use, such as arrayed waveguide gratings,<sup>1</sup> are complex to fabricate and relatively costly. Other demultiplexers include traditional dispersive devices, such as diffraction gratings and prisms. Although these other devices are much simpler and less expensive than arrayed waveguide gratings, they typically have an angular dispersion less than 1°/nm, which prevents them from being sufficiently compact. Recent work suggested that the superprism effect of periodic structures may provide a compact alternative, with angular dispersion many times higher than that of a conventional grating or prism. Zengerle<sup>2</sup> demonstrated this effect in singly and doubly periodic planar waveguides, and Kosaka *et al.*<sup>3</sup> used a three-dimensional photonic crystal structure. Additionally, related work was performed by other groups.<sup>4,5</sup> All these devices, however, are relatively complicated to fabricate. In this Letter we demonstrate experimentally that the same beam-steering effect exists in a simple one-dimensional (1D) dielectric stack structure, shown schematically in Fig. 1, and discuss its possible application within WDM systems.

Dielectric stacks are commonly used as mirrors.<sup>6</sup> Here, however, we deliberately operate at wavelengths just outside the main reflection band, where there is strong group-velocity dispersion and waves can still propagate through the structure. For a beam that is incident at an angle, this dispersion gives rise to a wavelength-dependent shift of the beam. This shift is possible because it is the group velocity, and not the phase velocity, that governs the energy flow of a light beam, and these two velocities can be dramatically different in a periodic structure. The average direction of energy propagation can be shown to be the same as the direction of group velocity

and is given by the normal to the constant-frequency dispersion diagram. The dispersion relation among  $K$  (the Bloch wave vector, in the direction perpendicular to the layers),  $\beta$  (the wave vector in the direction parallel to the layers), and optical angular frequency  $\omega$  for an infinite periodic dielectric stack is given by<sup>7</sup>

$$\cos(K\Lambda) = \cos(k_1a)\cos(k_2b) - \frac{1}{2}\gamma \sin(k_1a)\sin(k_2b), \quad (1)$$

where  $a$  and  $b$  are the thicknesses of layers with refractive indices  $n_1$  and  $n_2$ , respectively;  $\Lambda = a + b$ ;  $\gamma = (k_2/k_1 + k_1/k_2)$ ; and  $k_i = [(n_i\omega/c)^2 - \beta^2]^{1/2}$  ( $i = 1, 2$ ). Such a structure has a range of incident angles and wavelengths for which  $K$  is not real. These ranges correspond to total reflection, or, equivalently, to a 1D photonic bandgap. The form of the constant-frequency dispersion relation near the photonic band edge is shown in Fig. 2. This plot, also known as a wave-vector diagram, is a parametric plot of  $\text{Re}\{K\}$  and  $\beta$  for two different wavelengths near the structure's photonic band edge, from which the phase and the group velocity within the structure can be derived. As can be seen in the figure,

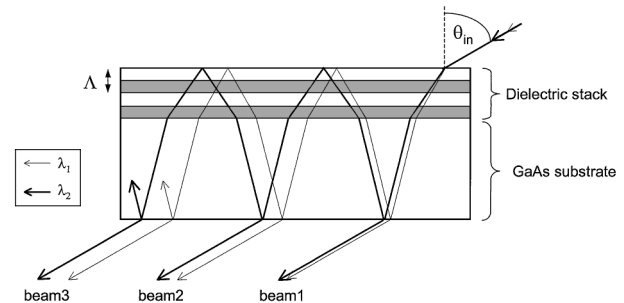


Fig. 1. Schematic of the device (not to scale). Only two periods are indicated. The beam paths of two different wavelengths are shown, including exiting beams resulting from 0, 2, and 4 bounces within the structure (beam1, beam2, and beam3, respectively). Polarization is perpendicular to the plane of the page.

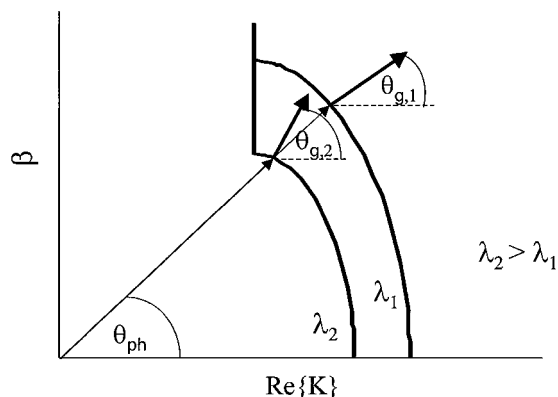


Fig. 2. Wave-vector diagram for two wavelengths near the band edge. Smaller arrows, direction of phase velocity; larger, thicker arrows, directions of group velocity.

light with a given incident angle, and therefore a given phase-velocity angle  $\theta_{ph}$ , will have different propagation angles within the structure for these two wavelengths. Near the photonic band edge (where, on the plot,  $\text{Re}\{K\}$  becomes constant), the propagation angle changes rapidly with wavelength. We can exploit this property to get a large beam-steering effect in the structure. That is, if a light beam composed of multiple near-gap wavelengths is incident at an angle on such a structure, different wavelengths will propagate through the dielectric stack with different angles and therefore become spatially separated. 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  $2^\circ/\text{nm}$  and in fact to approach infinity at the band edge. Note that a full photonic bandgap, that is, a bandgap for all incidence angles, is not necessary in this type of device.

The structure used in this experiment is a 30-period stack of alternating GaAs ( $n \cong 3.6$ ) and AlGaAs ( $n \cong 3.0$ ) layers, each 80 nm thick, grown upon a 500- $\mu\text{m}$ -thick GaAs substrate by molecular beam epitaxy. Because air and GaAs are both essentially isotropic materials, that is, the group and phase-velocity directions are essentially collinear, all angular separation of wavelengths that is due to group-velocity dispersion takes place in the 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 exit the sample, each a result of successive bounces between these mirrors. Hence we can use a multiple-bounce beam to obtain the wavelength separation corresponding to a thicker structure while simplifying the fabrication process by making the dielectric stack structure relatively thin.

A microscope objective was used to focus a beam of TE-polarized light from a tunable Ti:sapphire laser onto the sample, which was cleaved from near the edge of the wafer. The  $1/e^2$  diameter of the focused spot was approximately 10  $\mu\text{m}$ . The light transmitted through the sample was collected with a second lens. As we varied the wavelength of the laser, we then measured this transmitted light with a photodetector

to record transmission versus wavelength, allowing us to locate the wavelength range of interest. To measure the beam shift we imaged the transmitted light onto a CCD camera and analyzed the light with a digital oscilloscope.

A plot of beam position versus wavelength is shown in Fig. 3 for the primary transmitted beam, beam1. The theoretical curve was obtained by use of Bloch theory.<sup>7</sup> Over a range of 10 nm near the band edge, the position of the beam can be seen to shift by approximately 4  $\mu\text{m}$ . The discrepancy between the experimental data and the theoretical model could be attributed to three causes: First, the method used to fabricate the structure typically exhibits some unintentional chirp in layer thickness, which is not included in the model. Second, the Bloch model assumes incident plane waves at a given angle, whereas the experiment uses a tightly focused beam that in turn includes a range of angles. Finally, the Bloch model also assumes an infinite structure, whereas we have only 30 periods. Simulations performed with a transfer matrix approach show, however, that these beam-steering effects take place even for just a few periods and that 30 periods can be considered infinite.

In addition to the shift of this primary beam, we show the shifts of beam2 and beam3 in Fig. 4 to demonstrate the increase in shift for an equivalently thicker structure. The third beam shifted by over 30  $\mu\text{m}$  for the same 10-nm wavelength range. (A negligible portion of this shift—a few percent—is due to the change of refractive index with wavelength of the thick GaAs substrate.) Figure 5 shows the intensity profile of this third beam, which can be closely modeled as having a Gaussian beam profile, at two different wavelengths near the reflection edge. With a wavelength difference of 4 nm, the two beams are separated by approximately 12  $\mu\text{m}$ , greater than the  $1/e^2$  diameter 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 reaches the band edge

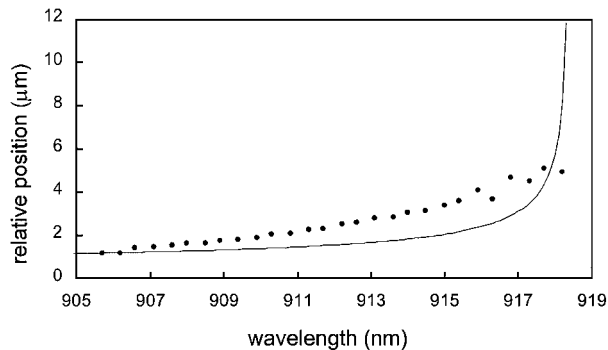


Fig. 3. Relative position of beam1 versus wavelength near the band edge for an incident angle in air of  $30^\circ$ . Filled circles, experimental data; solid curve, theoretical model for comparison. As the “zero” of position is arbitrary, the first data point is chosen to coincide with the theoretical curve.

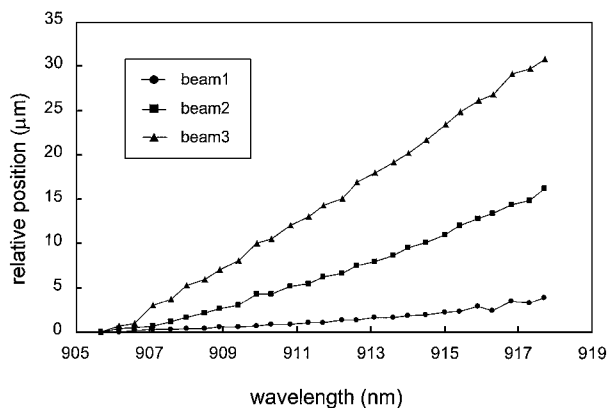


Fig. 4. Relative beam position versus wavelength near the band edge for beams with increasing numbers of reflections within the structure.

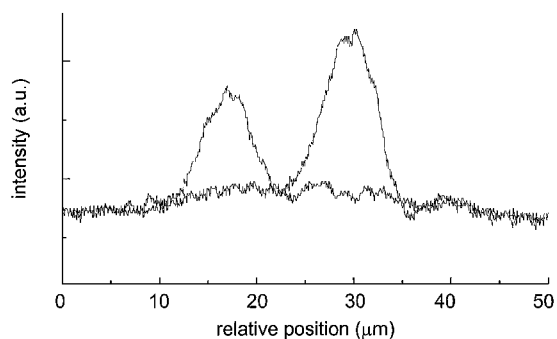


Fig. 5. Overlapped intensity versus position traces of two resolved beams. The left beam is at a wavelength of 909.2 nm, and the right beam is at 913.2 nm. The physical separation of the two beams is 12.3  $\mu\text{m}$ , and the two  $1/e^2$  beam widths are 10.4 and 10.9  $\mu\text{m}$ .

because of the group-velocity angular dispersion in the structure. Although the fringes are an artifact of the experimental setup and could be eliminated, the effect of beam broadening is an inherent property of the structure and could be a limiting factor when one is using such a device for wavelength separation. The two spatially separated beams in Fig. 5, however, are far enough from the reflection edge that they have had little or no broadening. We also expect that a device based on group-velocity dispersion would be polarization sensitive. This is because the wavelength of the reflection edge is slightly different for TE and TM polarizations, and so the two polarizations would undergo different amounts of shift at a given wavelength.

In this experiment the structure was used in transmission; however, at the wavelength range of interest the reflectivity of the stack is high. Therefore the power in the measured beams is rather low, particularly for the multiple-bounce beams. For a

single-bounce beam, the overall light efficiency was approximately 12% over the wavelength range measured, with the efficiency dropping off rapidly to only a few percent very near the reflection edge. One method of improving the efficiency of the device is to use it in reflection, with the beam incident upon the substrate side instead of on the dielectric stack. One could apply an additional reflector above the stack to ensure complete reflection from the upper side. The substrate could also be made highly reflective in the region in which the beams bounce by use of a metallic coating. A simple antireflection coating at the incident and exit regions of the substrate would further increase the efficiency of the device. Furthermore, such coatings would allow many more bounces within the structure, giving the greater wavelength separation required for a practical device. This will be the subject of future work.

We have demonstrated wavelength separation by use of a dielectric stack and suggested that one can exploit this fundamental property of 1D photonic crystals to create a compact, highly dispersive device for WDM. Unlike previous devices, this 1D structure is simple and inexpensive to fabricate and is made from readily available materials. In addition to epitaxial growth of semiconductor materials, similar structures could easily be made by more-conventional dielectric thin-film techniques. 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.

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