Tunable multichannel optical filter based on silicon photonic band gap materials actuation

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A Si-based tunable omnidirectional reflecting photonic band gap structure with a relatively large air gap defect is fabricated and measured. Using only one device, low-voltage tuning around two telecom wavelengths of 1.55 and 1.3 μm by electrostatic force is realized. Four widely spaced resonant modes within the photonic band gap are observed, which is in good agreement with numerical simulations. The whole process is at low temperature and can be compatible with current microelectronics process technology. There are several potential applications of this technology in wavelength division multiplexing devices.
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A large amount of research in recent years has focused on periodic dielectric materials possessing a photonic band gap (PBG), a range of frequencies within which the propagation of light is forbidden. PBG materials offer an unprecedented degree of control over light, which gives rise to a wide range of device applications in telecommunications and optoelectronics.[1,2] Specific applications proposed to date include but are not limited to waveguides with sharp turns, channel drop filters, microcavity waveguides, and photonic crystal fibers.[3–9] However, the functionality of many of these devices is limited by the fact that they must be manufactured to operate at a specific wavelength. Applications in telecommunications, such as wavelength division multiplexing, require the flexibility to operate at a large number of neighboring wavelengths. One promising strategy to address this problem is to create tunable PBG devices. Several groups have already proposed, and in some cases, begun designing and testing such devices.[10–14] Fabrication of a bulk three-dimensional periodic structure on the appropriate lengths scales with sufficient accuracy to retain a full PBG is a well-known, highly nontrivial experimental problem in its own right, let alone with the additional problem of introducing tunability—even though theoretical solutions to the latter have already been proposed. Fortunately, it has recently been demonstrated that one-dimensional periodic dielectric structures are capable of reflecting light from all incident angles and polarizations, under proper conditions.[15]

In this letter, we demonstrate a tunable one-dimensional PBG structure with large air defect size in silicon-based materials with an omnidirectional photonic band gap.[15] Using only one device, low voltage tuning around two telecom wavelengths of 1.55 and 1.3 μm is realized, which is important for multiple wavelength demultiplexing around both 1.55 and 1.3 μm.

The device studied in this letter consists of two quarter-wave stacks consisting of alternating layers of Si and SiO_2, separated by a tunable air gap. Each stack is theoretically predicted to have an omnidirectional reflecting frequency range between 20% and 30% of the midgap frequency. The period of the dielectric stack was chosen to create a band gap at the telecom wavelengths of 1.3 and 1.55 μm. A schematic illustration of this tunable PBG device is given in Fig. 1. It is fabricated, layer by layer, using the following procedure: first, a 260-nm-thick SiO_2 layer is deposited atop a (100) Si substrate by plasma enhanced chemical vapor deposition. A 110-nm-thick amorphous Si layer is then deposited on top by electron beam. Two more identical bilayers are then added, followed by another identical layer of SiO_2. Next, a sacrificial layer of polyimide is spin coated on top. The entire structure made up to this point is cured at a relatively high temperature, then cooled. After cooling, the top dielectric stack is deposited on top of the polyimide with the same specifications as for the bottom dielectric stack. Next, a film with a low Young's modulus is deposited opposite the Si substrate to serve as a supporting membrane. Lithography is used to pattern the resulting structure and form the air gap in selected areas. Application of a voltage between the membrane and substrate can tune the cavity thickness.

The reflectivity spectrum of this device was measured using a Nicolet 860 Fourier-transform infrared spectrometer (FTIR) at room temperature. A sample measurement of this device is shown in Fig. 2(a). The results were unchanged under small temperature variations of about $\pm 5°$, up to ex-

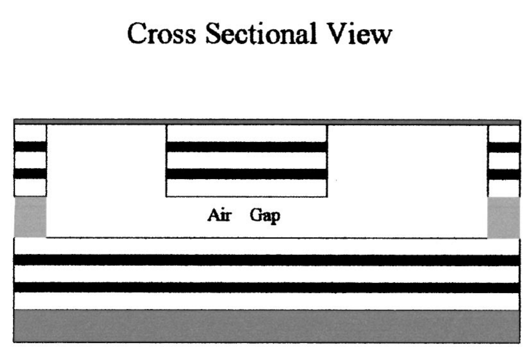

FIG. 1. Illustration of the one-dimensional photonic band gap structure with large air cavity. The two quarter-wave stacks are composed of SiO_2/Si pairs, which are separated by an air gap with thickness of 4.8 μm.

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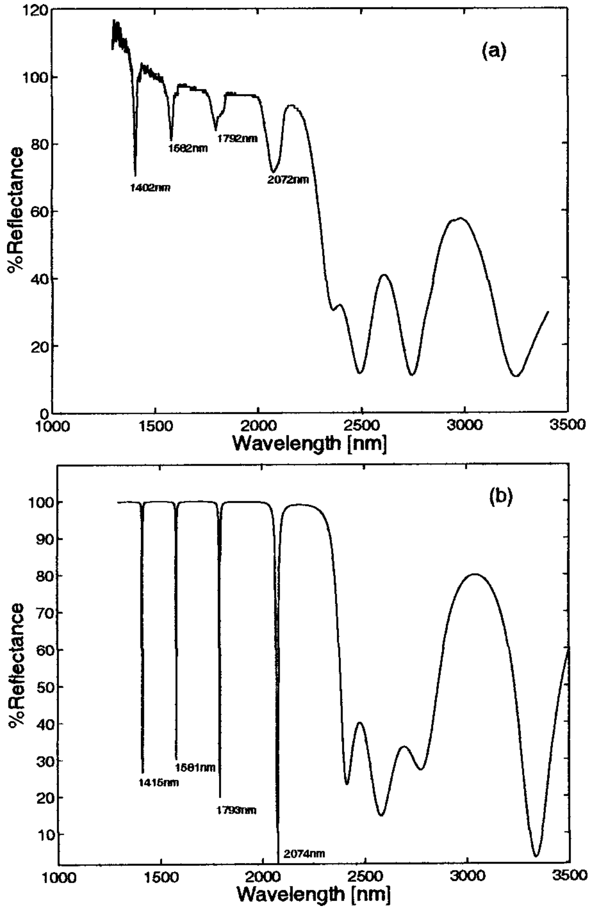

FIG. 2. (a) The measured reflectivity spectrum by FTIR, the four resonance modes within the photonic band gap are 1.402, 1.582, 1.792, and 2.072 μm. The PBG range is from 1.19 to 2.18 μm according to simulation, the shorter wavelength spectrum not shown here is due to the weak FTIR photodetector responsivity. (b) The numerical simulation of the structure, which shows the resonance modes within the photonic band gap at 1.415, 1.581, 1.793, and 2.074 μm, which is in agreement with measurement in the FTIR measurement wavelength range.

perimental resolution. The FTIR was calibrated relative to the reflectivity of Au at that wavelength. The photonic band gap at normal incidence is very large, extending from 1.19 to 2.18 μm. Four dips in the reflectivity spectrum falling within the PBG were observed to be centered at the wavelengths 1.402, 1.582, 1.792, and 2.072 μm. The position of these

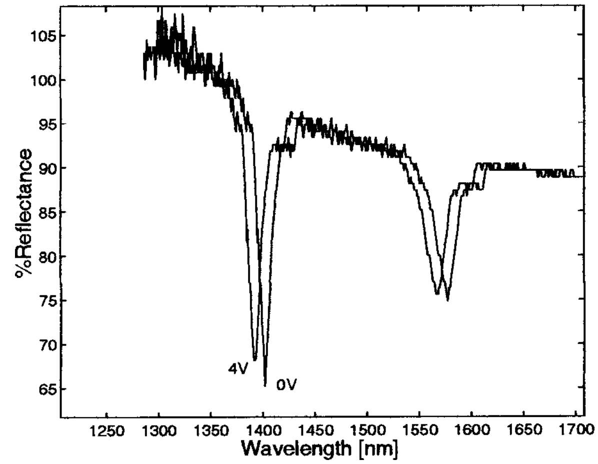

FIG. 4. The resonance modes at 0 and 4 V in the 1.2–1.7 μm windows, the resonance modes are shifted at 1.582 and 1.402 μm when 4 V are applied.

dips is in good agreement with two independent numerical calculations. First, a finite-difference time-domain (FDTD) simulation of Maxwell's equations was performed in order to produce the reflection spectrum shown in Fig. 2(b).[16] Second, eigenmodes of Maxwell's equations with periodic boundary conditions were computed by preconditioned conjugate-gradient minimization of the block Rayleigh quotient in a planewave basis, using a freely available software package. This calculation was used to create a projected band structure for both TM and TE modes (left- and right-hand sides, respectively), which is shown in Fig. 3. It was confirmed that the modes at zero transverse wave vector, corresponding to normal incidence, are centered at the same wavelengths as the results from the time-domain simulation. The dips in the reflectance can then be understood as resonant modes, analogous to the defect modes of a doped semiconductor.

Application of a voltage also allows for tuning of the resonant modes, as illustrated in Fig. 4, where the spectra resulting from two different applied voltages are superimposed. For an applied voltage of 0 V, two resonant modes are observed at the wavelengths 1.402 and 1.582 μm. Application of 4 V shifts these modes to the wavelengths 1.392 and 1.568 μm. In Fig. 5, the wavelength shift is plotted against the applied voltage squared. The observed linear relationship

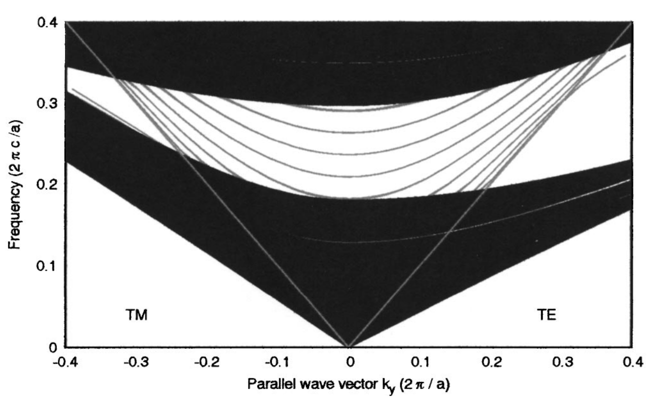

FIG. 3. The projected band structure of the one-dimensional photonic crystal with air cavity with the light line ($\omega = ck_y$), showing an omnidirectional reflectance range for both TM and TE modes (left- and right-hand sides, respectively) and multiple localized states within the band gap.

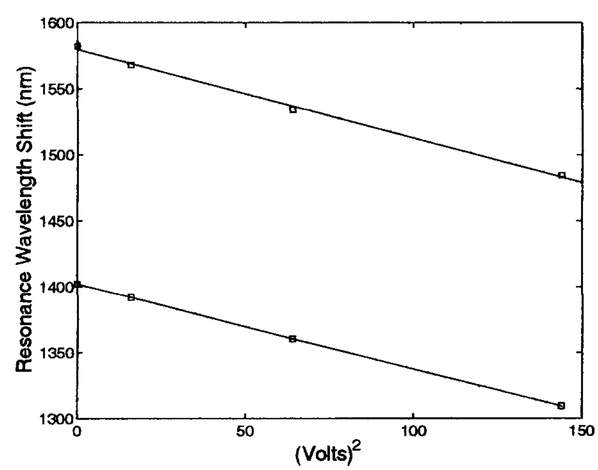

FIG. 5. The resonance wavelength shift with applied voltage square at 1.582 and 1.402 μm.

between these two quantities is consistent with the mechanism of electrostatic tuning of the localized modes. The figure also shows that an applied voltage of 10 V can produce a shift of nearly 60 nm for the 1.582 μm resonance. A shift of this order of magnitude should be sufficient to enable switching and modulation in telecommunication devices.

For resonant modes observed around the wavelengths 1.402 and 1.582 μm, the quality factors (''Q's'') were measured to be approximately 94 and 79, respectively. The Q's found in the FDTD simulation were considerably higher, 943 and 988, respectively. The Q of the fabricated structures can be degraded by: (1) mirror reflectivities; (2) mirror absorption, (there is no absorption in the air gap); and (3) deviations from parallel mirrors with no curvature. In this report, the main contribution to fabricated Q less than theoretical Q is mirror curvature. This diagnosis is evident in the resonance signal asymmetry on the long wavelength side, suggesting a convex curvature resulting from a compressive stress. Using a staircase correlation function, we estimate the radius of curvature of the mirror from the broadening at the resonance wavelength around 1.582 μm, which is about 20 nm, to be 0.7 cm.

It is interesting to note that two of these resonances are within the standard telecommunications wavelength spectrum. Additionally, the free spectral range of this PBG device (more than 100 nm) is very large. The tuning is coupled and not independent for the two wavelengths, so only one of the two wavelengths is expected to be used in a basic deployment. One might envision an array of identically fabricated devices functioning in several wavelength regions.

In conclusion, Si-based tunable, omnidirectional photonic band gap devices were designed, fabricated, and measured. The large 1 μm band gap at normal incidence served to allow for widely spaced resonant modes, with one near 1.3 and one near 1.55 μm, two wavelengths of interest in telecommunications. Low voltage tuning of these resonant modes was achieved, with a maximum shift of nearly 60 nm for an applied voltage of 10 V.

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