

A Dielectric Omnidirectional Near-infrared Reflector

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We have studied both theoretically and experimentally an omnidirectional reflector operating at the wavelength region of 1.3 μ m. The omnidirectional reflector, a special case of one-dimensional photonic crystals, was prepared by alternately sputtering two dielectric materials, amorphous silicon and silicon dioxide. Measured reflectance spectra, very consistent with simulated results at all angles and polarizations, clearly showed the existence of an omnidirectional photonic bandgap.

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I. INTRODUCTION

A dielectric reflector has many advantages such as lower loss, higher reflectivity, and higher mechanical robustness over its metallic counterpart. Moreover, the location and width of stopband of a dielectric reflector can be controlled by structural design parameters such as layer thickness and refractive index. In spite of many advantages, a dielectric reflector is functional only for a certain range of incident angles of light. So as to overcome this drawback of the dielectric reflector, researchers recently introduced a new type of dielectric reflector, *the omnidirectional reflector* [1]-[4], based on the concept of the photonic crystal (PC) [5]. A photonic crystal is a structure in which the refractive index is three-dimensionally (3D) modulated in a periodic manner. A photonic crystal provides a whole different mechanism of controlling light [6]. Owing to the periodic nature, a photonic crystal may possess a photonic bandgap (PBG) in which there is no traveling photonic state regardless of propagation direction and polarization of light, much like an electronic bandgap observed in semiconductors. A recent finding is that under certain conditions even a simple one-dimensional (1D) PC, a periodic multilayer structure, can play role of an ideal 3D PC in terms of its reflection behavior. Since there is no allowed photon

propagation state, the 1D PC reflects light incident at any possible angle and polarization, resulting in omnidirectional reflectance.

In this letter, we introduce an omnidirectional reflector consisting of amorphous silicon (α -Si) and silicon dioxide (SiO_2), whose omnidirectionality in reflection spans over the near-infrared wavelength range around 1.3 μ m. We describe its design, fabrication, and reflectance spectrum measurements. The measured spectra as a function of incidence angle and polarization are compared with theoretical simulations.

II. OMNIDIRECTIONAL REFLECTOR DESIGN

The model structure for an omnidirectional reflector is a semi-infinite 1D PC system that consists of two alternating layers whose refractive indices and thickness are (n_1, d_1) and (n_2, d_2) . The terminated side of the structure is faced to a medium whose refractive index is n_0 . In an infinitely periodic layer structure, there exists a translational symmetry and its solution to Maxwell's equations is described as the Bloch wave. Applying the well-known transfer matrix method [7] to the one-dimensional periodic structure, the exact form of Bloch wavevector can be written as

$$K(\beta, \omega) = \frac{1}{\Lambda} \cos^{-1} \left[\cos(k_1 d_1) \cos(k_2 d_2) - \frac{1}{2} \left(\frac{\xi_2 k_1}{\xi_1 k_2} + \frac{\xi_1 k_2}{\xi_2 k_1} \right) \sin(k_1 d_1) \sin(k_2 d_2) \right] \quad (1)$$

where $k_i = \sqrt{(\frac{\omega n_i}{c})^2 - \beta^2}$ ($i = 1$ or 2) is the wavevector component perpendicular to the layer plane, while c , ω , β are the velocity of light, angular frequency, and the wavevector component parallel to the layer plane, respectively. For an electromagnetic wave incident at an angle one needs to consider two polarization situations, transverse-electric (TE) and transverse-magnetic (TM) polarizations. The parameter ξ_i in Eq. (1) differs for each polarization: 1 for TE and n_i^2 for TM.

According to Eq. (1), the Bloch wave can be made either propagating or evanescent. If the Bloch wavevector K is purely imaginary, the corresponding Bloch wave becomes evanescent and thus decays exponentially as it penetrates into the 1D PC structure, which is the basis of the PBG effect [5]. If there exists a frequency range for which K becomes imaginary so that the PBG effect is sustained regardless of incidence angle and polarization, then the PC prohibits propagation of the Bloch wave completely. Then the incident light is subject to 100% reflection in that frequency range, and the resultant reflectance of the 1D PC approaches unity regardless of the angle and polarization of incident light, leading to the omnidirectional reflectivity.

The frequency range for the omnidirectional reflection behavior can be controlled with a number of structural parameters. As a detailed calculation example, Fig. 1 shows the projected band diagram for a 1D PC model structure in which ($n_1=3.52$, $d_1=260$ nm) and ($n_2=1.45$, $d_2=250$ nm). n_1 and n_2 are the refractive indices of α -Si and SiO_2 , typical in the near-

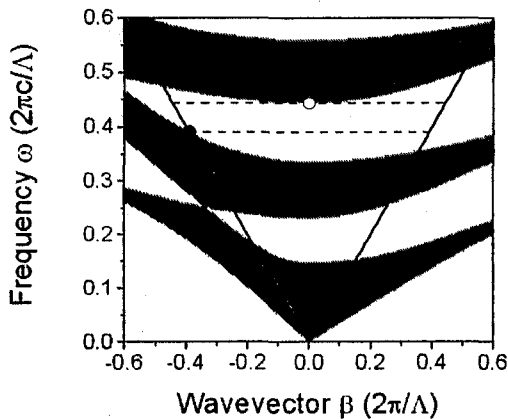


FIG. 1. Projected band diagram of the one-dimensional photonic crystal reflector. The refractive indices and layer thickness are assumed to be ($n_1=3.52$, $d_1=260$ nm) and ($n_2=1.45$, $d_2=250$ nm). The gray and white regions indicate propagation and forbidden photon states, respectively. The lines in the diagonal directions identify the edges of the light cone. The region inside the dashed lines and light lines represents the omnidirectional band.

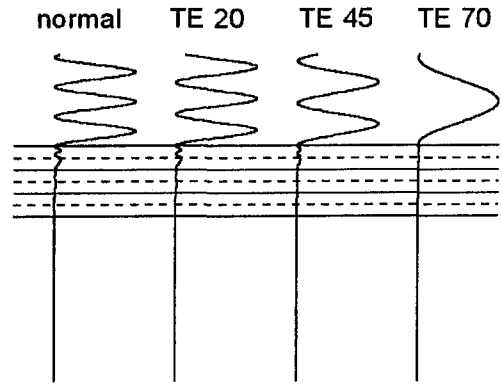


FIG. 2. Calculated field profiles at the interface between the air and the one-dimensional photonic crystal reflector for four different incidence angles. The space between two adjacent solid lines represents one layer pair while each dashed line indicates the interface between α -Si and SiO_2 .

infrared frequencies. In Fig. 1, the positive (negative) β corresponds to the case of TE (TM) polarization. The gray regions represent the allowed photon states so that the Bloch waves can propagate through the structure whereas the white regions represent the prohibited states (or the PBGs) and the corresponding Bloch waves are totally reflected from the structure. These white areas representing the forbidden states are the places where the omnidirectionally reflecting function is to be built. Since our target wavelength is $1.3 \mu\text{m}$, which is translated into $\omega = 0.392 \times (2\pi c/\Lambda)$, we are bounded within the second bandgap.

The dispersion relation of an electromagnetic wave in the incident medium (air in our case), on the other hand, can be written as $\omega = c(k_0^2 + \beta^2)^{1/2}$, where k_0 and β are the wavevector components perpendicular and parallel to the layer plane, respectively, in the medium. The condition $\omega > c\beta$ must be satisfied for ω to be real and only the region above the lightline defined by $\omega = c\beta$ has physical meanings in the projected band diagram. In our model structure, therefore, the frequency region for the omnidirectional reflection is defined by the two dashed lines at $\omega = 0.39 \times (2\pi c/\Lambda)$ and $\omega = 0.44 \times (2\pi c/\Lambda)$, as shown in Fig. 1. These two boundary lines are determined by two critical points: (1) the solid circle at $\omega = 0.39 \times (2\pi c/\Lambda)$ and $\beta = -0.39 \times (2\pi/\Lambda)$ as the lower bound and (2) the open circle at $\omega = 0.44 \times (2\pi c/\Lambda)$ and $\beta = 0 \times (2\pi/\Lambda)$ as the upper bound.

The choice of the two constituent materials, α -Si and SiO_2 , is made for the following reasons: (1) the two materials are most common in micro-fabrications; (2) they are non-absorptive at the $1.3 \mu\text{m}$ region and therefore serve as pure dielectrics; and (3) their refrac-

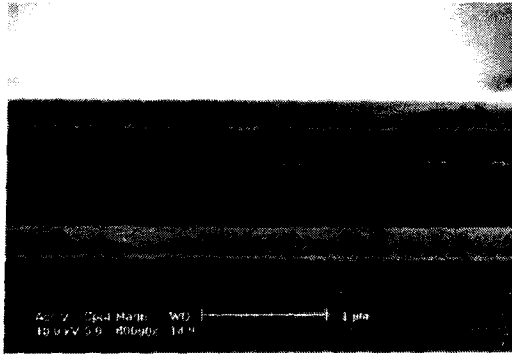


FIG. 3. A cross-sectional SEM image of the fabricated omnidirectional reflector consisting of three pairs of α -Si and SiO_2 . The lighter layers are α -Si while the darker layers correspond to SiO_2 .

tive index contrast is large. The last issue is quite important from a design point of view. The larger the refractive index contrast is, the larger the imaginary value of the corresponding Bloch wavevector in Eq. (1). A large imaginary Bloch wavevector in turn implies rapid field decay inside the 1D PC structure, requiring fewer layer pairs in realizing the 1D PC. Fig. 2 compares calculated field profiles for light incident at different angles. In general, the Bloch wave incident at a larger angle decays faster in the reflector, and therefore penetrates a smaller depth. From this figure one can safely conclude that three pairs of α -Si and SiO_2 are sufficient to play the role of an ideal semi-infinite 1D PC in practical sense.

III. EXPERIMENTS AND DISCUSSION

We fabricated an omnidirectional reflector that operates at the telecommunications wavelength of around $1.3\mu\text{m}$. Detailed design issues including the materials choice and layer numbers are as explained in the previous section. Three pairs of α -Si and SiO_2 layers were alternately deposited by RF-sputter method with their nominal thickness being $d_1=260\text{nm}$ and $d_2=250\text{nm}$, respectively. Shown in Fig. 3 is the cross-sectional SEM image of the fabricated omnidirectional reflector structure. It turns out that their actual thickness slightly fluctuates from their nominal values, but the nature of the omnidirectional reflector is not significantly affected as demonstrated by the final results. In other words, fabrication tolerance in layer thickness is quite huge as long as index contrast is large enough.

Measuring the absolute value of reflectance is always challenging. An indirect method that is commonly exercised when the mirror reflectivity is close to unity is to form a cavity by sandwiching a spacer layer between

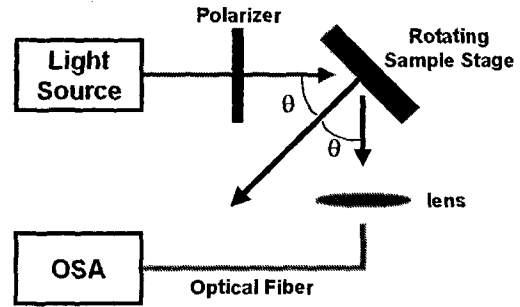


FIG. 4. Schematic diagram of the measurement setup for reflectance spectrum.

a pair of mirrors and measure its cavity quality factor. More important in the omnidirectional reflector is however the spectral range of omnidirectional high reflectance (or stopband). Therefore we investigated reflectance spectra as a function of incident beam angle and compared them with theoretically predicted ones. Fig. 4 schematically illustrates the experimental setup used for the reflectance spectrum measurements. White light from a halogen lamp is collimated into a few millimeter-sized light beam, which then passes a polarizer and shines on the sample surface. The sample is mounted on a rotational stage so that the light incidence angle can be varied. The reflected light beam is fed into a spectrum analyzer through a multi-

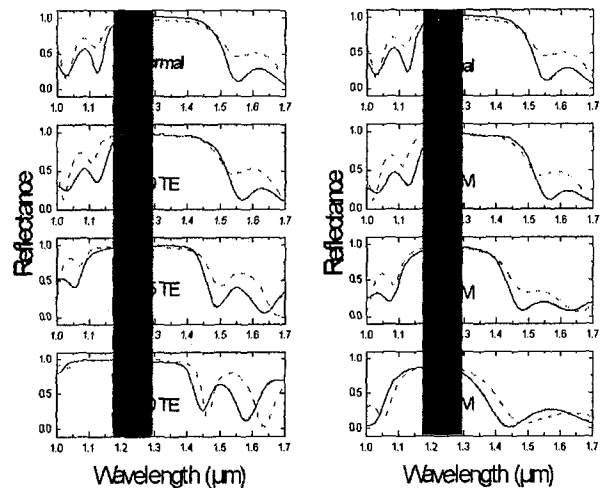


FIG. 5. Reflectance spectra of the omnidirectional reflector. Spectra shown in the left (right) column are for TE (TM) polarization. The solid lines represent the measured reflectance spectra whereas the dashed lines are the simulated ones. The gray area indicates the omnidirectional spectral region.

mode fiber. In our measurements, reflectance spectra were calibrated using a combination of 1.3 μm laser diode and silver-coated mirror.

The incident angles were varied over 0° (normal), 20° , 45° , and 70° for each polarization (TE or TM). The measured reflectance spectra, presented in Fig. 5, were observed to obey the general trends that theories predict. The dashed lines in Fig. 5 show simulated reflectance spectra that are obtained by the transfer matrix method [7]. There is a good agreement between the measured reflectance spectra and the simulation results, proving the high quality of the fabricated reflector. As predicted by the theoretical band diagram shown in Fig. 1, the measured high reflectance plateau or stopband is indeed gradually shifted toward the shorter wavelength for both polarizations as the tilt angle becomes larger. In addition, the high reflectance bandwidth gets wider for the TE polarized light whereas it gets narrower for the TM-polarized. Most importantly, we observed clearly the existence of an omnidirectional reflectance band, the spectral region for which reflectance is close to unity regardless of the angle and polarization of incident light, as indicated by the gray area in Fig. 5.

IV. CONCLUSION

We have designed, fabricated, and characterized a near-infrared (around 1.3 μm in wavelength) omnidirectional reflector based on 1D PC. Owing to the large refractive index contrast between two constituent materials, $\alpha\text{-Si}$ and SiO_2 , the omnidirectionality in reflectance is fully established. Based on simulated field profiles, three pairs of layers are found to be more than enough for realization of a practical omnidirectional reflector. Multiple layers of $\alpha\text{-Si}$ and

SiO_2 were RF-sputter-deposited, and the reflectance spectra were measured for four different incidence angles of 0° (normal), 20° , 45° , and 70° for both TE and TM polarizations. The measured spectra agreed very well with simulated reflectance spectra based on the transfer matrix method, indicative of successful realization of an omnidirectional reflector. Possible applications of the developed omnidirectional reflector include the measurement standard in optics experiments for all angles and polarization in the wavelength range around 1.3 μm . Also, it could provide a platform for new types of 1D PC waveguides with ultra low loss.

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