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A Dielectric Omnidirectional Reflector
Yoel Fink, Joshua N. Winn, Shanhui Fan, Chiping Chen, Jurgen Michel, John D. Ioannopoulos, Edwin L. Thomas*

A design criterion that permits truly omnidirectional re flectivity for all polarizations of incident light over a wide selectable range of frequencies was used in fabricating an all-dielectric omnidirectional reflector consisting of multilayer films. The reflector was simply constructed as a stack of nine alternating micrometer-thick layers of polystyrene and tellurium and demonstrates omnidirectional reflection over the wavelength range from 10 to 15 micrometers. Because the omnidirectionality criterion is general, it can be used to design omnidirectional reflectors in many frequency ranges of interest. Potential uses depend on the geometry of the system. For example, coating of an end mirror will result in an optical cavity. A hollow tube will produce a low-loss, broadband waveguide, whereas a planar film could be used as an effi cient radiative heat barrier or collector in thermoelectric devices.

Mirrors, probably the most prevalent of optical devices, are used for imaging and solar energy collection and in laser cavities. One can distinguish between two types of mirrors, the age-old metallic and the more recent dielectric. Metallic mirrors reflect light over a broad range of frequencies incident from arbitrary angles (that is, omnidirectional re flectance). However, at infrared and optical frequencies, a few percent of the incident power is typically lost because of absorption. Multilayer dielectric mirrors are used primarily to reflect a narrow range of frequencies incident from a particular angle or particular angular range. Unlike their metallic counterparts, dielectric reflectors can be extremely low loss. The ability to reflect light of arbitrary angle of incidence for all-dielectric structures has been associated with the existence of a...
complete photonic band gap (1–3), which can exist only in a system with a dielectric function that is periodic along three orthogonal directions. In fact, a recent theoretical analysis predicted that a sufficient condition for the achievement of omnidirectional reflection in a periodic system with an interface is the existence of an overlapping band gap regime in phase space above the light cone of the ambient media (4). Now we extend the theoretical analysis and provide experimental realization of a multilayer omnidirectional reflector operable in infrared frequencies. The structure is made of thin layers of materials with different dielectric constants (polystyrene and tellurium) and combines characteristic features of both the metallic and dielectric mirrors. It offers metallic-like omnidirectional reflectivity together with frequency selectivity and low-loss behavior typical of multilayer dielectrics.

We consider a system that is made of an array of alternating dielectric layers coupled to a homogeneous medium, characterized by $n_0$ (such as air with $n_0 = 1$), at the interface. Electromagnetic waves are incident upon the multilayer film from the homogeneous medium. Although such a system has been analyzed extensively in the literature (5–7), the possibility of omnidirectional reflectivity was not recognized until recently. The generic system is described by the index of refraction profile in Fig. 1, where $h_1$ and $h_2$ are the layer thickness and $n_1$ and $n_2$ are the indices of refraction of the respective layers. The incident wave has a wave vector $\mathbf{k} = k_x \mathbf{\hat{x}} + k_y \mathbf{\hat{y}}$ and a frequency of $\omega = c|k|/n_0$, where $c$ is the speed of light in vacuum and $\mathbf{\hat{x}}$ and $\mathbf{\hat{y}}$ are unit vectors in the $x$ and $y$ directions, respectively. The wave vector together with the normal to the periodic structure defines a mirror plane of symmetry that allows us to distinguish between two independent electromagnetic modes: transverse electric (TE) modes and transverse magnetic (TM) modes. For the TE mode, the electric field is perpendicular to the plane, as is the magnetic field for the TM mode. The distribution of the electric field of the TE mode (or the magnetic field in the TM mode) in a particular layer within the stratified structure can be written as a sum of two plane waves traveling in opposite directions. The amplitudes of the two plane waves in a particular layer $\alpha$ of one cell are related to the amplitudes in the same layer of an adjacent cell by a unitary $2 \times 2$ translation matrix $U^{\alpha}$ (7).

General features of the transport properties of the finite structure can be understood when the properties of the infinite structure are elucidated. In a structure with an infinite number of layers, translational symmetry along the direction perpendicular to the layers leads to Bloch wave solutions of the form

$$E_K(x,y) = E_K(x)e^{ikx}e^{iky}$$  (1)

where $E_K(x, y)$ is a field component, $E_K(x)$ is periodic, with a period of length $a$, and $K$ is the Bloch wave number given by

$$K = \frac{i}{a} \ln \left( \frac{1}{2} \mathrm{Tr}(U^{\alpha}) \right) \pm \sqrt{\left( \frac{1}{4} [\mathrm{Tr}(U^{\alpha})]^2 - 1 \right)} \right)^{1/2}$$  (2)

Solutions of the infinite system can be propagating or evanescent, corresponding...
The multilayer system leading to Fig. 2A represents a structure with a limited reflectivity cone because for any frequency one can always find a \( k_x \) vector for which a wave at that frequency can propagate in the crystal and hence transmit through the film. For example, a wave with \( \omega = 0.285 \times 2\pi \nu/a \) (dashed horizontal line in Fig. 2A) will be reflected for a range of \( k \) values ranging from 0 (normal incidence) to \( 0.285 \times 2\pi \nu/a \) (90° incidence) in the TE mode, whereas in the TM mode it begins to transmit at a value of \( k_x = 0.187 \times 2\pi \nu/a \) (−41° incidence). The necessary and sufficient criterion (8) for omnidirectional reflectivity at a given frequency is that no transmitting state of the structure exists inside the light cone; this criterion is satisfied if frequency ranges marked in dark gray in Fig. 2B. In fact, the system leading to Fig. 2B exhibits two omnidirectional reflectivity ranges.

The omnidirectional range is defined from above by the normal incidence band edge \( \omega_0(k_x = \pi/a, k_y = 0) \) (point a in Fig. 2B) and from below by the intersection of the top of the TM allowed band edge with the light line \( \omega(k_x = \pi/a, k_y = \omega/c) \) (point b in Fig. 2B).

The exact expression for the band edges is

\[
\frac{1 + \Lambda}{2} \cos(k_x^{(1)}h_1 + k_x^{(2)}h_2) + 1 - \frac{1 - \Lambda}{2} \cos(k_x^{(1)}h_1 - k_x^{(2)}h_2) + 1 = 0, \tag{3}
\]

where \( k_x^{(\omega)} = \sqrt{(\omega n/c)^2 - k_y^2} \) (\( \omega = 1, 2 \)) and

\[
\Lambda = \begin{cases} 
1 & k_x^{(2)} < k_x^{(1)} \quad \text{TE} \\
\frac{1}{2} \frac{k_x^{(1)} + k_x^{(2)}}{k_x^{(2)} - k_x^{(1)}} & \text{TM} \\
\frac{1}{2} \frac{n_2^2 k_x^{(1)} - n_1^2 k_x^{(2)}}{n_2^2 k_x^{(1)} + n_1^2 k_x^{(2)}} & \text{TM}
\end{cases} \tag{4}
\]

A dimensionless parameter used to quantify the extent of the omnidirectional range is the ratio of midrange ratio defined as \( (\omega_0 - \omega)/\sqrt{(\omega_0 + \omega)} \). Figure 3 is a plot of this ratio as a function of \( \omega_0/n_1 \) and \( n_1/n_0 \), where \( \omega_0 \) and \( \omega \) are determined by solutions of Eq. 3 with quarter wave layer thickness. The contours in this figure represent various equi omnidirectional ranges for different material index parameters and could be useful for design purposes.

It may also be useful to have an approximate analytical expression for the extent of the gap. This can be obtained by setting \( \cos(k_x^{(1)}h_1 - k_x^{(2)}h_2) = 1 \) in Eq. 3. We find that for a given incident angle \( \theta_0 \), the approximate width in frequency is

\[
\Delta \omega(\theta_0) = \frac{2c}{h_1 + n_1^2 - n_1^2 \sin^2 \theta_0 + h_2 + n_2^2 - n_2^2 \sin^2 \theta_0} \times \left[ \cos^{-1}\left(\frac{\Lambda - 1}{\Lambda + 1}\right) - \cos^{-1}\left(\frac{\Lambda - 1}{\Lambda + 1}\right) \right]. \tag{5}
\]

At normal incidence, there is no distinction between TM and TE modes. At increasingly oblique angles, the gap of the TE mode increases, whereas the gap of the TM mode decreases. In addition, the center of the gap shifts to higher frequencies. Therefore, the
criterion for the existence of omnidirectional reflectivity can be restated as the occurrence of a frequency overlap between the gap at normal incidence and the gap of the TM mode at 90°. Analytical expressions for the range to midrange ratio can be obtained by setting
\[
\omega_b = \frac{2c}{h_2n_2 + h_1n_1}\cos^2 \left(\frac{n_1 - n_2}{n_1 + n_2}\right)
\]
where \(\omega_b\) is the midrange frequency and \(\omega_m\) is the lower frequency edge of the omnidirectional range. The angle of incidence that satisfies the condition for omnidirectional reflectivity is given by
\[
\sin \theta = \frac{\sqrt{n_1^2 - n_2^2}}{n_1 + n_2}
\]

Moreover, the maximum range width is attained for thickness values that are not equal to the quarter wave stack although the increase in band width gained by deviating from the quarter wave stack is typically only a few percent (4).

In general, the TM mode defines the lower frequency edge of the omnidirectional range. An example can be seen in Fig. 2B for a particular choice of the indices of refraction. This can be proven by showing that
\[
\frac{\partial \omega}{\partial k_T} \mid_{TM} \geq \frac{\partial \omega}{\partial k_T} \mid_{TE}
\]
in the region that resides inside the light line. The physical reason for Eq. 7 lies in the vectorial nature of the electric field. In the upper portion of the first band, the electric field concentrates its energy in the high dielectric regions. Away from normal incidence, the electric field in the TM mode has a component in the direction of periodicity, and this component forces a larger portion of the electric field into the low dielectric regions. The group velocity of the TM mode is therefore enhanced. In contrast, the electric field of the TE mode is always perpendicular to the direction of periodicity and can concentrate its energy primarily in the high dielectric region.

A poly styrene-tellurium (PS-Te) materials system was chosen to demonstrate omnidirectional reflectivity. Tellurium has a high index of refraction and low loss characteristics in the frequency range of interest. In addition, its relatively low latent heat of condensation together with the high glass transition temperature of the PS minimizes diffusion of Te into the polymer layer. The choice of PS, which has a series of absorption peaks in the measurement range (9), demonstrates the competition between reflectivity and absorption that occurs when an absorption peak is located in the evanescent state region. The TE (0.8 μm) and PS (1.65 μm) films were deposited (10) sequentially to create a nine-layer film (11).

The optical response of this particular multilayer film was designed to have a high reflectivity region in the 10- to 15-μm range for any angle of incidence (in the experiment, we measure from 0° to 80°). The optical response at oblique angles of incidence was measured with a Fourier Transform Infrared Spectrometer ( Nicolet 860) fitted with a polarizer (ZnS, SpectraTech) and an angular reflectivity stage (VeeMax; SpectraTech). At normal incidence, the reflectivity was measured with a Nicolet Infrared Microscope. A freshly evaporated aluminum mirror was used as a background for the reflectance measurements.

A good agreement between the calculated (12) and measured reflectance spectra at normal, 45°, and 80° incidence for the TM and TE modes is shown in Fig. 4. The regimes of high reflectivity at the different angles of incidence overlap, thus forming a reflective range of frequencies for light of any angle of incidence. The frequency location of the omnidirectional range is determined by the layer thickness and can be tuned to meet specifications. The range is calculated from Eq. 6 to be 5.6 μm, and the center wavelength is 12.4 μm, corresponding to a 45% range to midrange ratio shown in dashed lines in Fig. 3 for the experimental index of refraction parameters. These values are in agreement with the measured data. The calculations are for lossless media and therefore do not predict the PS absorption band at ~ 13 and 14 μm. The PS absorption peak is seen to increase at larger angles of incidence for the TM mode and to decrease for the TE mode. The physical basis for these phenomena lies in the relation between the penetration depth and the amount of absorption. The penetration depth is \(\xi \propto \text{Im}(1/K)\), where \(K\) is the Bloch wave number. It can be shown that \(\xi\) is a monotonically increasing function of the incident angle for the TM mode of an omnidirectional reflector and is relatively constant for the TE mode. Thus, the TM mode penetrates deeper into the structure at increasing angles of incidence (Table 1) and is more readily absorbed. The magnitude of the imaginary part of the Bloch wave number for a mode lying in the gap is related to its distance from the band edges. This distance increases in the TE mode because of the widening of the gap at increasing angles of incidence and decreases in the TM mode because of the shrinking of the gap.

Table 1. Penetration depth (\(\xi\)) at different angles of incidence for the TE and TM modes.

<table>
<thead>
<tr>
<th>Angle of incidence (degrees)</th>
<th>(\xi_{TM}) (μm)</th>
<th>(\xi_{TE}) (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.51</td>
<td>2.51</td>
</tr>
<tr>
<td>45</td>
<td>3.05</td>
<td>2.43</td>
</tr>
<tr>
<td>80</td>
<td>4.60</td>
<td>2.39</td>
</tr>
</tbody>
</table>

The PS-Te structure does not have a complete photonic band gap. Its omnidirectional reflectivity is due instead to the restricted phase space available to the propagating states of the system. The materials and processes were chosen for their low cost and applicability to large area coverage. The possibility of achieving omnidirectional reflectivity itself is not associated with any particular choice of materials and can be applied to many wavelengths of interest. Our structure offers metallic-like omnidirectional reflectivity for a wide range of frequencies and at the same time is of low loss. In addition, it allows the flexibility of frequency selection.

References and Notes

2. S. John, ibid., p. 2486.
8. A necessary condition for omnidirectional reflectivity is that light from outside the film cannot be allowed to access the Brewster angle \(\theta_B = \tan^{-1}(n/n\_r)\) of the multilayer structure because at this angle the TM mode will be transmitted through. This condition is met when the Brewster line lies outside of the light line or in the refractive indices of the layers \(\sin^{-1}(n/n\_r) < \theta_B\). A sufficient condition is the existence of a particular frequency at which no propagating mode within the crystal exists between \(k_n = 0\) and \(k_n = n\_o\omega/c\). Figure 2A is an example of a structure that does not have an omnidirectional re- flectivity range even though its Brewster crossing is inaccessible to light coming from the homogeneous medium (the Brewster crossing lies outside the light cone). This is due to the large group velocity of modes in the lower band edge of the TM mode that allow every frequency to couple to a propagating state in the crystal. This should be contrasted with Fig. 2B, which exhibits omnidirectional reflectivity over a range [highlighted in dark grey]; the high indices of refraction actually allow for the opening of an additional omnidirectional reflectivity range in the higher harmonic as well.
10. A 0.8 ± 0.09-μm-thick layer of tellurium (99.99% + Strem Chemicals) was vacuum evaporated at 10−6 torr and 7A (Ladd Industries 30000) onto a NaCl 25-mm salt substrate (polished NaCl window; Willard Glass). The layer thickness and deposition rate were monitored in situ with a crystal thickness monitor (Sycon STM1000). A 10% solution of poly styrene (GoodYear PS standard, 110,000 g/mol) in toluene was spin cast at 1000 rpm onto the tellurium-coated substrate and allowed to dry for a few hours; the polymer layer thickness is 1.65 ± 0.09 μm.
11. The nine-layer film sequence was Te/PS/Te/PS/Te/PS/PS/Te/PS/Te.
12. The calculations were done with the transfer matrix method described in (5) with the film parameters.