All-Dielectric One-Dimensional Periodic Structures for Total Omnidirectional Reflection and Partial Spontaneous Emission Control

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Abstract—A remarkable property of one-dimensional (1-D) all-dielectric periodic structures has recently been reported, namely, a 1-D structure can totally reflect electromagnetic wave of any polarization at all angles within a prescribed frequency region. Unlike their metallic counterpart, such all-dielectric omnidirectional mirrors are nearly free of loss at optical frequencies. Here we discuss the physics, design criteria and applications of the thin-film all-dielectric omnidirectional mirror. The experimental demonstration of the mirror is presented at optical frequencies.

Index Terms—Dielectric mirror, photonic crystal, photonic bandgap (PBG), spontaneous emission control.

I. INTRODUCTION

It is well known that spontaneous emission can be strongly modified by changing the environment near an excited atom. A microcavity with perfectly reflecting walls can considerably inhibit or enhance spontaneous emission of atoms placed inside it [1], [2].

Metallic mirrors being a good reflector for any angle of incidence fulfill the requirements to be inside walls of microcavities. At optical frequencies there however is a problem with them: they display notable dissipative losses.

Photonic crystals were originally proposed by Yablonovitch [3] to fix this problem. Photonic crystals are periodically microstructured dielectric materials which can exhibit the frequency bands that are completely free of electromagnetic states. The forbidden band is usually referred to as a full three-dimensional (3-D) photonic bandgap (PBG). Being made from positive-dielectric-constant materials photonic crystal can be almost free of dissipative losses at any prescribed frequency. In the limit of a thick sample photonic crystal behaves as an omnidirectional high reflector.

Since the first works [3], [4], the concept of photonic crystal has been attracting close attention of the scientific community and a lot of applications have been proposed (see [2], [5]–[9] and refs. therein).

However, until now the possibility to design an all-dielectric microstructure displaying total omnidirectional reflection has mainly been associated with 3-D periodic materials. In spite of current success in the microstructuring of 3-D photonic crystals [10]–[13], there is still a serious technological problem to fabricate a periodic structure of arbitrary wavelength-scale period. The investigations of low dimensional periodic media have been attracting considerable interest.

It has recently been recognized, that two-dimensional (2-D) [14] and one-dimensional (1-D) [15]–[20] periodic structures can display some features of full 3-D PBG, namely, display total omnidirectional reflection of arbitrary polarized wave within certain frequency region.

A 1-D photonic crystal is nothing other than the well-known dielectric Bragg mirror consisting of alternating layers of low, $n_1$, and high, $n_2$, indexes of refraction. $d_1$ and $d_2$ are the thicknesses of the layers. $n$ is a reflective index of an ambient medium. The light rays refracting and propagating through a stack are presented. The full domain of incident angles $\alpha_{in} \in [-\pi/2, \pi/2]$ is mapped into the internal cone of half-angle $\alpha_{inn} = \arcsin n/n_1$ (the light gray area). For sufficiently large index ratio $\delta n_0 = n_2/n_1$ the internal cone’s half-angle $\alpha_{inn}$ may be smaller than the Brewster angle $\alpha_B$. An externally incident wave can never couple to the Brewster window.

Fig. 1. Schematic representation of a dielectric multilayer structure of alternating layers of low, $n_1$, and high, $n_2$, indexes of refraction. $d_1$ and $d_2$ are the thicknesses of the layers. $n$ is a reflective index of an ambient medium.
The paper is organized as follows. Section II outlines the origin of the total omnidirectional reflection displayed by 1-D photonic crystals. Optimization criteria of the mirror design are reported. The possibility of partial spontaneous emission control is discussed. In Section III, the experimental demonstration of the mirror is presented at optical frequencies.

II. THEORETICAL RESULTS

A. Total Omnidirectional Reflection

Consider an infinite periodic stack of alternating layers of low, \( n_1 \), and high, \( n_2 \), indexes of refraction and the thicknesses \( d_1 \) and \( d_2 \), respectively (Fig. 1). The period is \( \Lambda = d_1 + d_2 \). The periodicity of the structure leads to the Bloch wave solutions of the Maxwell equations. The Bloch wave number \( K \) may be obtained from the dispersion relation (see, e.g., [21] and [22])

\[
K(k_{\perp},\omega)\Lambda = \pi \cos \left( \frac{\pi}{2}(A + D) \right)
\]

(1)

where \( k_{\perp} \) is the tangential component of the Bloch wave vector, \( \omega \) is the frequency. A particular form of the quantities \( A \) and \( D \) may be found elsewhere [21], [22]. Due to the planar geometry of the problem, the separation of the electromagnetic field into transverse electric (TE) and transverse magnetic (TM) polarization states is possible, where the electric or magnetic field vector, respectively, is parallel to the layers interfaces. This splits the problem into the two independent ones for TE and TM polarizations, respectively.

Photonic band structure of an infinite system of layers is depicted in Fig. 2. The refractive indexes, \( n_1 = 1.4 \) and \( n_2 = 3.4 \), are chosen close to ones of SiO\(_2\) and Si in the near IR region, where these materials are essentially transparent. The band structure has been calculated using the dispersion relation (1). The left panel is for TE polarization, and the right one for TM. An infinite periodic structure can support both propagating and evanescent Bloch waves, depending on real or imaginary Bloch wave numbers are. In Fig. 2, gray areas correspond to the propagating states, whereas white areas contain the evanescent states only and are usually referred to as PBG’s.

As only the normal component of the wave vector is involved in the bandgaps formation for oblique propagation, the bandgaps shift toward the higher frequencies with the tangential component of the wave vector (Fig. 2). The common feature of the band structure of 1-D lattices is that the forbidden gaps are always closed up (e.g., the crossed circles in Fig. 2). Another feature of the band structure is that the TM forbidden gaps shrink to zero onto the Brewster light-line, where \( \omega = c|k_{\perp}/n_2 \sin \alpha_B | \) (Fig. 2), \( \alpha_B = \arctan n_2/n_1 \) is the Brewster angle. The TM polarized wave propagates without any reflection from \( n_2 \) to \( n_1 \) layer, and from \( n_1 \) to \( n_2 \) layer, at the Brewster angle \( \alpha_B \).

Suppose that the plane electromagnetic wave illuminates the boundary of a semi-infinite periodic stack under the angle, \( \alpha_{\text{inc}} \), from semi-infinite homogeneous medium of refractive index, \( n \) (Fig. 1). While the frequency and the wave vector of an incident wave are fitted into the forbidden gaps of the photonic crystal, an incident wave undergoes total reflection. The bandgaps of the crystal lead to the total reflection bands in the spectra, which are very sensitive to the incident angle. Two questions arise: 1) whether it is possible to avoid the coupling of the incident wave to the Brewster window, where the reflection coefficient at the interface of low, \( n_1 \), and high, \( n_2 \), index layers is identically zero and 2) whether the reflection bands (PBG’s) can be wide enough to be open for all incident angles.

When electromagnetic wave illuminates the boundary of the semi-infinite crystal, the possible values of the internal angles are restricted by the Snell’s law. The full domain of incident angles \([-\pi/2, \pi/2]\) is mapped into the internal cone of half-angle \( \alpha_{\text{inc}} \), \( \alpha_{\text{inc}} = \arcsin n/n_1 \) (the light gray area in Fig. 1). The larger are refractive indexes of the layers with respect

1 It is important to note that infinite and semi-infinite photonic crystals have the same band structure [23], the only difference is the existence of surface modes in the case of semi-infinite stack.
to the medium outside the crystal, the narrower is a cone of internal angles. For sufficiently large index ratio $\delta n_0 = n_1/n$, the internal cone’s half-angle $\alpha_{\text{inc}}^{\text{max}}$ can be smaller than the Brewster angle $\alpha_B$. An externally incident wave will never couple to the Brewster window. This answers the first question.

To answer the second question, consider the reduced region of k-space associated with the ambient medium (Fig. 2). For an incident wave with the wave vector $|\mathbf{k}| = n\omega/c$, the tangential component of the wave vector remains constant throughout the crystal and equals to $|\mathbf{k}_\perp| = (n_2/\epsilon_2)\bar{n}\sin \alpha_{\text{inc}}$. Here, $\alpha_{\text{inc}}$ is incident angle, $\omega$ is the frequency and $c$ is the speed of light in vacuum. The wave coming from the outside can only excite the states lying above the ambient-medium light-line (solid line in Fig. 2 corresponds to the ambient medium with refractive index $n = 1$). To have an omnidirectional reflection the forbidden gap should be open within this reduced region of $k$-space. A sufficiently large index ratio $\delta n = n_2/n_1$ can make a trick, leading to the wide bandgap opened for all incident angles.

For the structure presented (Fig. 2) and air as an ambient medium, $n = 1$, both index ratio $\delta n = n_2/n_1 \approx 2.4$ and $\delta n_0 = n_1/n = 1.4$ are sufficiently large, so the first two overall bandgaps are open for all external angles of incidence. No propagating mode are allowed in the stack for any propagating mode in the ambient medium within the gaps for both TE and TM polarizations (shaded areas in Fig. 2). The total omnidirectional reflection arises. A band of surface modes lies below the ambient-medium light-line [9] and thus surface modes do not affect the external reflectivity.

It is instructive also to represent the band structure in terms of internal angles. An internal angle parametrizes the tangential component of the wave vector as $|\mathbf{k}_\perp| = (n_2\omega/c)\sin \alpha_{\text{int}}$, where $n_2$ is the reflective index of the layer, $\alpha_{\text{int}}$ is the internal angle in the $n_2$ layer. In Fig. 3 the band structure is redrawn in terms of internal angles in the low index layer. One can see that the overall forbidden gap is opened for all external incident angles for both fundamental polarizations forming an omnidirectional total reflection band (gray area in Fig. 3).

B. Optimization Criteria

To design an omnidirectional mirror, one needs to have total reflection for all incident angles and all polarization states. The TM PBG is narrower than TE one and so defines the bandwidth of an omnidirectional reflection band. The upper edge of the reflection band corresponds to the upper edge of the forbidden gap at normal incidence. The lower edge is defined by the intersection of the ambient-medium light-line with the upper edge of the corresponding TM band (Fig. 2). For given parameters of the periodic structure, the refractive index of an
ambient medium may be used to control the bandwidth. By increasing the refractive index of an ambient medium from $n = 1$ to some $n = n_{\text{max}}$ the bandwidth decreases till an omnidirectional reflection band is closed up. In Fig. 4 the maximum refractive index of the ambient medium $n_{\text{max}}$, for which the first omnidirectional reflection band is closed up, is presented as a function of the index ratio $\delta n$ for various values of the refractive index of the low index layer $n_2$ and the fixed filling fraction $\eta = d_2/\Lambda = 0.5$.

The filling fraction $\eta = d_2/\Lambda$ optimizes the relative bandwidth $\Delta\omega/\omega_0$ of an omnidirectional reflection band with respect to the given refractive indexes of the layers constituting the 1-D photonic crystal and the index of an ambient medium. Here $\Delta\omega$ is the width of the omnidirectional reflection band and $\omega_0$ is the central frequency. In Fig. 5 an overall bandgaps leading to the omnidirectional total reflection bands are presented versus the filling fraction. For the first overall bandgap, gaps corresponding to the normal and grazing incidence are presented. The solid curves are for normal incidence. The dashed (dotted) curves are for grazing incidence for TE (TM) polarization. The omnidirectional reflection band, which is due to the overlap of the gaps corresponding to the normal and grazing incidence, is depicted as the shaded area. The omnidirectional reflection bands of the higher order are opened. The inset (Fig. 5) shows relative bandwidth of the first total reflection band versus filling fraction. There is a clear optimum filling fraction $\eta_{\text{opt}}$ leading to the maximum of the relative bandwidth.

We further present the set of contour plots (Fig. 6) which provides the full information about the first omnidirectional total reflection band for given parameters of the system. An optimal filling fraction and corresponding central frequency are shown in Fig. 6(a) and (b), respectively, as a function of the index ratio $\delta n$ for different values of index ratio $\delta n_0$. The dashed curve in Fig. 6(a) corresponds to the filling factor of a quarter-wave stack, which is $\eta_{\text{opt}} = 1/(1 + \delta n)$. Within a given parameter range a quarter-wave stack is not an optimal configuration to reach a maximum relative bandwidth for the omnidirectional reflection band, however it gives the relative bandwidth which is usually few percent smaller than optimal one [Fig. 6(c)]. In Fig. 6(c) the optimal relative bandwidth is depicted as a function of the index ratio $\delta n_0$. A wide omnidirectional total reflection band exists for reasonable values of both $\delta n_1$ and $\delta n_0$. To obtain an omnidirectional band with bandwidth larger than 5% the index ratios should be larger than 1.5 ($\delta n_1 > 1.5, \delta n_0 > 1.5$). A decrease in one of the index ratios is partially compensated by an increase in the other one.
For the SiO$_2$/Si ($n_1 = 1.4$, $n_2 = 3.4$) structure in air ($n = 1.0$) the omnidirectional reflection band is centered at the normalized frequency $\omega A/2\pi c = 0.275$ with the optimal filling fraction $n_{\text{fill}} = 0.324$. The relative bandwidth is about 25%. To obtain an omnidirectional reflection centered at the radiation wavelength $\lambda$, one needs a period of the structure of about 0.412 $\mu$m.

C. Perfect Mirror or More?

To suppress substantially the spontaneous emission of radiating species placed inside the layer of a periodic stack, the layer must be free of all unbound and bound modes. For the structure presented (Fig. 3) an overall forbidden gap is open up to the grazing angles in the case of TE polarized radiation, while an overall forbidden gap is closed up at near 60° of an internal angle for TM polarization. The internal angle in the low index layer, for which an overall forbidden gap is closed up, is presented in Fig. 7 as a function of the index ratio $\delta n$. Black dot corresponds to the stack parameters as in Fig. 3: $n_1 = 1.4$, $n_2 = 3.4$. For all index ratios $\delta n$ which are to the right of the dashed vertical line, an overall TE forbidden gap is open for all internal angles. For such design parameters, the low index layer of the structure can be completely free of TE polarized propagating modes. To ensure the layer is free of all modes, bound modes, which are essentially guided modes, should be absent as well. However, there be no modes within the low index layer which can couple to the high-index-layer modes, including guided modes [21]. The radiation of emitting species embedded in low index layer may be inhibited over about $\pm 60°$ aperture of internal angles (Fig. 3).

Prospects for partial spontaneous emission control using this kind of 1-D periodic structures are discussed in [19]: Introducing a low index defect layer Russell et al. resolve the Brewster window problem, namely design a defect layer which may be free of all unbound and bound modes. Properly designed defect layer may provide the emission control over a solid angle $4\pi$ steradian.

III. EXPERIMENTAL RESULTS

We have chosen to check theoretical predictions at optical wavelengths. A lattice consisting of 19 layers of Na$_3$AlF$_6$ and ZnSe ($n_1 = 1.34$ and $n_2 = 2.5$–2.8 correspondingly) was fabricated by standard optical technology using layer by layer deposition of the materials on a glass substrate. The multilayer stack was terminated at both ends with ZnSe layer. The thickness of each layer was $d_1 = d_2 = 90$ nm. An omnidirectional total reflection was expected within the spectral band $\Delta \lambda = 604.3–638.4$ nm with relative bandwidth of 5.3%.

Transmission spectra for TE- and TM-polarizations at different incident angles in the range of 0–60° were measured using a “Cary 500” spectrophotometer (right panel in Fig. 8). The calculated transmission spectra are depicted in the left panel of Fig. 8, a good agreement is obtained. From Fig. 8 one can see that for spectral range from 600 to 700 nm the transmission coefficient is very low for both polarizations. The absolute values of transmission for TE-polarization in
Transmission coefficient of Na₃AlF₆/ZnSe structure on angles of incidence at wavelength of 632.8 nm (HeNe laser) for two polarizations of incident light. For TM-polarization circles are directly measured transmission coefficients, squares mark transmission coefficients calculated from reflection measurement data. For TE-polarization (upper triangles) the signal at angles more than 60° is out of the sensitivity range of the experimental set-up. The solid (dashed) curve is the theoretically calculated transmission coefficient for TE- (TM-) polarized light. The dotted curve corresponds to the transmission coefficient of the structure terminated at both ends with low index layer, Na₃AlF₆, for TM-polarized light.

IV. Conclusions

In summary, we have demonstrated the possibility to achieve a total omnidirectional reflection with 1-D periodic dielectric structures. The origins of the total omnidirectional reflection have been discussed. Optimization criteria of omnidirectional totally reflecting mirror design have been presented. We have found that for reasonable values of structure parameters ($\delta n > 1.5$, $\delta n_0 > 1.5$) a relatively large omnidirectional total reflection band (>5%) may be obtained, making the fabrication of a “perfect” all-dielectric thin-film mirror feasible. The possibility of partial spontaneous emission control with 1-D periodic structures has been discussed. The experimental demonstration of the mirror has been presented at optical frequencies.

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