Experimental Measurement of the Effect of Termination on Surface Electromagnetic Waves in One-Dimensional Photonic Bandgap Arrays

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Abstract— **Two different attenuated total-internal reflection prism configurations are used to explore the excitation of surface electromagnetic waves on one-dimensional (1-D) photonic bandgap (PBG) arrays. The effect of surface termination of the photonic crystal is shown to have a significant effect on the dispersion of the surface modes excited at that interface. The results show that it is possible to engineer the position of the surface mode within the forbidden bandgap. Modes that are located close to the center of the bandgap are shown to be more localized, leading to significantly higher surface electromagnetic fields than modes located near the band edge. The existence of surface modes can have an effect on many of the proposed applications for PBG materials. The modes are also of interest in their own right for use in applications such as sensors and modulators.**

Index Terms— **Dielectric materials, electromagnetic propagation in nonhomogeneous media, electromagnetic surface waves, optical surface waves, thin films.**

I. Introduction and Motivation

SURFACE electromagnetic waves (SEW's) have long been recognized and studied as a fundamental excitation at the interface between two suitably active media. Surface waves are typically nonradiative modes propagating along an interface with amplitudes that are evanescent in each bounding medium. In the continuum approximation, in which the electromagnetic response of two media i and j can be described by dielectric functions ε_i and ε_j, respectively, the condition governing the existence of surface waves is that $\varepsilon_i/\varepsilon_j < -1$. This relation implies that one of the two media forming the interface has a dielectric function that is negative at the frequency of interest. A negative dielectric constant is typically encountered in association with strong absorption; thus, surface electromagnetic waves are sought at the interfaces of metals at frequencies in the infrared or visible, or in ionic crystals at frequencies above the reststrahl region.

In dielectric arrays designed to exhibit photonic bandgaps (PBG's), the collective effects of scattering and interference lead to an attenuating material whose *effective* dielectric constant is negative at frequencies within the forbidden band. Thus, it is possible to excite surface modes at the interface of PBG arrays. Various authors have considered this problem theoretically in arrays of one [1]–[3] and higher [4] dimensions. Experiments to observe surface waves have also been performed in one-dimensional (1-D) arrays at optical wavelengths [5], [6] and in two-dimensional [7] arrays in the microwave regime. In this paper, we describe optical frequency experiments that demonstrate the use of prism coupling to excite surface waves; we determine their dispersion relation and explore the effect of surface termination on 1-D PBG arrays. The motivation for the study of surface electromagnetic waves in PBG materials is twofold. First, because the surface modes offer an intraband energy loss mechanism, they can impact many of the proposed applications of PBG materials. Second, the surface waves are of interest in their own right for their potential use in sensors, modulators, atom mirrors, and in the enhancement of surface nonlinear optical effects. For applications that make use of SEW's, PBG's are appealing because it is possible to engineer a sample that exhibits a bandgap (and hence surface waves) within any frequency range without depending on intrinsic material properties. Furthermore, because PBG materials are constructed from pure dielectrics, their loss is very low. This low loss is a generally desirable property in SEW applications because it leads to narrow coupling resonances and high surface-electromagnetic (EM) fields.

II. Experimental Configuration

In the experiments described here, an attenuated total-internal-reflection prism configuration was used to couple light to the surface modes on 1-D dielectric stacks with different surface terminations. As the experiment and the ensuing data analysis demonstrate, the termination of the photonic crystal has a profound effect on the nature of the surface modes. We chose to use 1-D PBG arrays—Bragg quarter-wave reflectors consisting of alternating layers of high and low refractive index materials—because they are easy to fabricate. The essential physics should be equally applicable to PBG arrays of higher dimensions. Two different samples were used in these experiments. Each consisted of alternating layers of 247 nm of SiO_2 and 169 nm of TiO_2 deposited on glass slides. These

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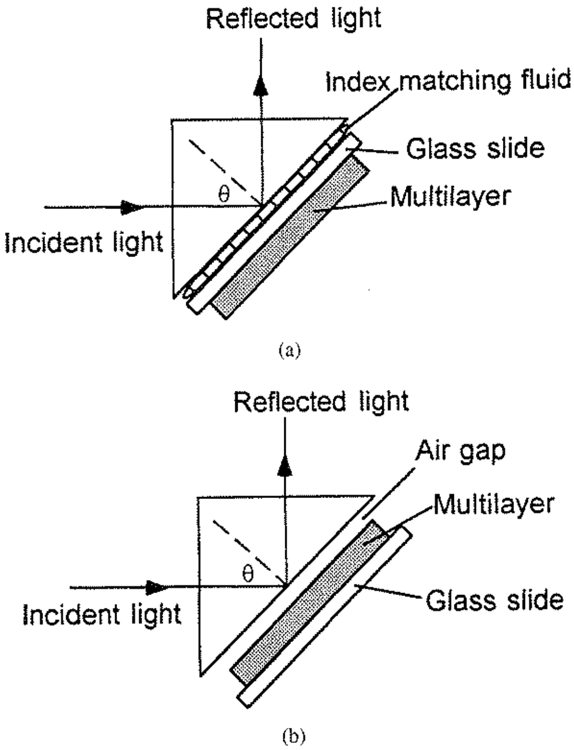


Fig. 1. Attenuated total-internal reflection prism configurations. (a) Kretschmann geometry in which the active medium is directly contacted to the reflecting face of the prism. Surface waves are generated at the interface of the PBG materials and the air. (b) Otto configuration in which an air gap of about a wavelength is maintained between the reflecting face of the prism and the surface at which surface waves are excited.

parameters correspond to a Bragg reflector with a normal incidence stop band centered at about 1.4 μm. The important difference between the samples was in the termination of the last layer deposited. One sample was terminated with a complete bilayer of TiO_2/SiO_2, whereas the second was terminated with an additional 85 nm of TiO_2, half the thickness of the other TiO_2 layers in the sample.

Theory [2], [3] predicts that nonradiative surface waves should exist at the interface of each of the two samples. However, it is not possible to couple light in air directly into a surface mode because the wave vector of the surface excitation at each frequency lies beyond the light line. This phase matching problem is similar to that encountered in the excitation of surface plasmons in thin metal films [8], and we chose the same method adopted in those experiments—attenuated total-internal-reflection prism coupling—to facilitate optical excitation of surface waves. Two different prism-coupling configurations were used, as dictated by the requirements of each sample. The different configurations are illustrated in Fig. 1. Fig. 1(a) shows the so-called Kretschmann configuration [9], in which the glass substrate is contacted directly to the prism with an intervening layer of index matching fluid. The refractive index of the prism must be close to that of the glass substrate so that the substrate becomes an effective extension of the prism. At angles greater than total internal reflection, there is an evanescent field that penetrates through the PBG layer. If the frequency and parallel wave vector of the evanescent field match that of a surface mode at the PBG/air interface, then light, which would normally be total-internally reflected, couples instead to the surface mode, resulting in a reflectivity drop. The dispersion of the surface mode is determined from the frequency f of the incident light and from the parallel wave vector k of the mode, which is given by

$$k = \frac{2\pi f}{c} n \sin\theta$$

where n is the index of the prism, c is the speed of light, and θ is the angle at which the reflectivity dip occurs.

The Kretschmann configuration is easy to work with, and it is particularly useful for applications. However, the restriction to prism indexes that are of the same order as the glass substrate places an upper limit on the parallel wave vector range that can be explored. To probe larger wave vectors requires the use of a higher index prism. In the Kretschmann case, the high index prism sees the index matching fluid/glass substrate as a low index medium at which total internal reflection (TIR) can occur, isolating the light from reaching the PBG layer. This difficulty could be circumvented by depositing the multilayer on a high index substrate or directly onto the reflecting face of the high index prism. However, in order to use the available samples, we employed the prism geometry known as the Otto configuration [10], illustrated in Fig. 1(b). In this case, a small air gap is maintained between the reflecting face of the prism and the surface of the PBG sample. The gap width is selected such that the surface is located within the evanescent fields at the reflecting face of the prism. The gap adjustment is accomplished using a micrometer that presses the PBG sample into the reflecting face of the prism.

This configuration is clearly less desirable for a couple of experimental reasons. First, it is very hard to adjust or to measure the air gap with any precision. Second, the nonuniformity of the air gap across the face of the prism means that a relatively small area of illumination must be used. In our experiments a long focal length lens was used to focus the laser light to a small spot. The act of focusing introduces a spread of angles, and a concomitant spread of wave vectors in the incident light. Because the reflectivity dips can be very sharp, the small spread in angles results in an undesirable broadening and a decrease in depth of the reflectivity minimum.

Measurement of the angular reflectivity in either the Kretschmann or the Otto configurations was accomplished by mounting the corresponding configuration on a computer-controlled rotation stage. A second rotation stage, mounted coaxially with the first, controlled the motion of a photodiode. The stage rotations were programmed such that the reflected beam was always intercepted by the photodiode. The optical source used in these experiments was a tunable diode laser whose wavelength could be adjusted over the wavelength range from 835 to 860 nm. In all experiments, the laser light incident on the sample was s-polarized. The optical beam was chopped and the signal from the photodiode fed to a lock-in amplifier. The data acquisition and control computer digitized the output signal of the lock-in amplifier.

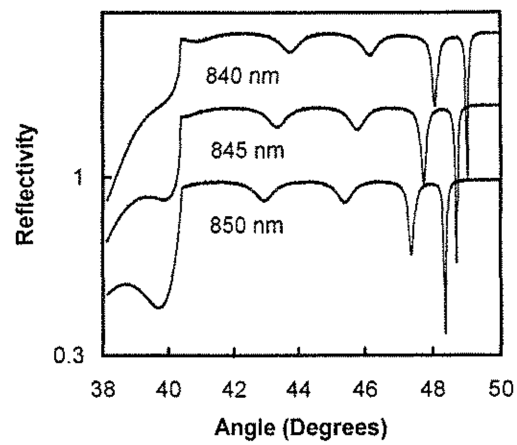


Fig. 2. Reflectivity data acquired with the Kretschmann configuration at three different wavelengths for the fully terminated 1-D multilayer. The reflectivity data have been offset for clarity. The narrow mode at the largest angle corresponds to the surface mode; the other three reflectivity dips are due to leaky guided waves in the multilayer.

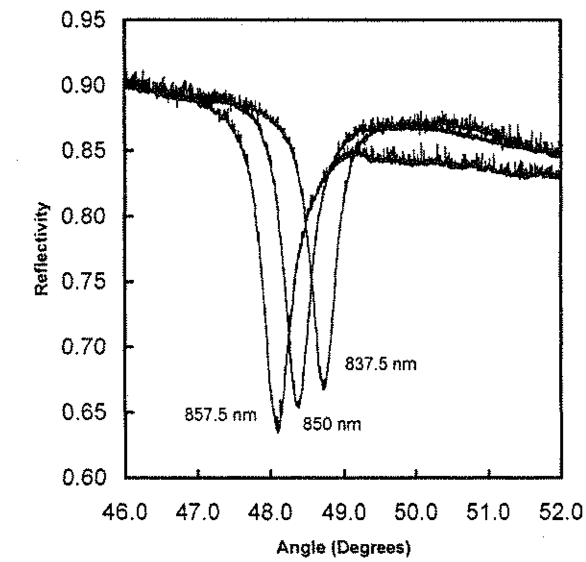


Fig. 3. Reflectivity data acquired in the Otto configuration at three different wavelengths for the half-layer terminated 1-D multilayer. A high index prism was used to acquire these reflectivity curves.

III. Experimental Results

Fig. 2 shows typical reflectivity data for the Kretschmann configuration using the sample that had a complete layer termination. The horizontal scale refers to the internal angle of incidence within the prism. The cusp at 40.3° corresponds to the angle of TIR between the prism and air. At larger angles, there are four reflectivity dips. As discussed in the analysis below, the deepest, narrow dip at the largest angle corresponds to the surface mode propagating at the PBG/air boundary, and the other three modes correspond to leaky guided waves within the PBG layer. For this termination, the surface mode exists just within the forbidden gap just below the upper band edge. Close to the band edge, the attenuation of the PBG material is relatively weak so that the light is able to tunnel through the 15 bilayers that make up the PBG material and to excite the surface mode.

In the sample that had a half-layer termination, theory [2], [3] predicts that the surface mode will be moved more deeply into the bandgap and thus to a much higher parallel wave vector. To access this large wave vector range required the use of a high index gadolinium gallium garnet prism ($n = 1.951$ at this wavelength range). As explained previously, the high index prism also necessitated the use of the Otto prism configuration. Fig. 3 shows the reflectivity data for this sample. The figure plots only a small angular range in the vicinity of the reflectivity dips for three different wavelengths over the tuning range of the laser; there is only this one reflectivity dip per wavelength in the angular range from TIR up to the angles shown.

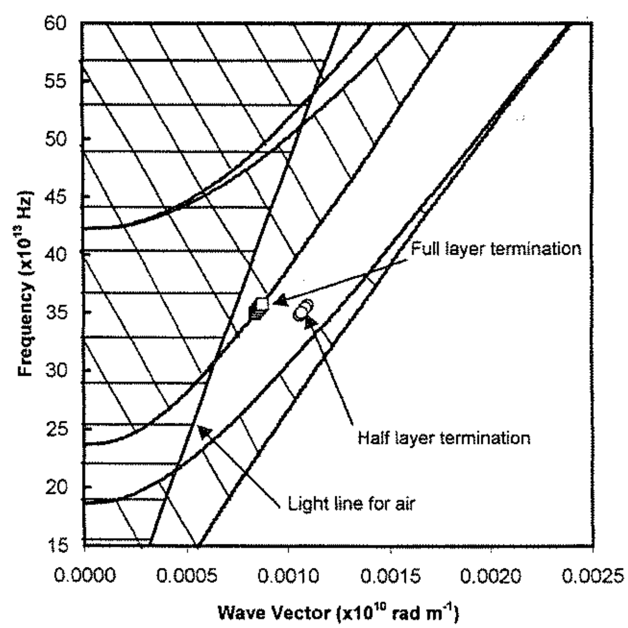


Fig. 4. The surface dispersion diagram showing frequency-wave vector regions that are radiative into the air side of the interface (horizontal hatching) and into the multilayer (diagonal hatching). Also plotted on the surface dispersion diagram is the experimentally determined surface-wave dispersion over the tuning range of the laser. The circles correspond to the half-layer terminated sample, whereas the squares correspond to the full-layer terminated sample.

IV. Relation of Experimentally Determined Surface-Wave Dispersion to the Photonic Band Structure

To relate the surface-wave dispersion results obtained from the experiment to the photonic band structure of the multilayer sample, it is useful to plot a dispersion diagram of frequency versus wave vector projected into the plane of the interface. Such plots have been usefully employed in previous theoretical analyses of surface modes in PBG arrays [2]–[4]. A surface dispersion plot for our multilayer dielectric samples is shown in Fig. 4. The figure can best be interpreted by first considering the horizontally hatched region that corresponds to surface-wave vector values that are radiative on the air side of the interface. Light at any given frequency can have wave vector values ranging from zero (normal incidence) up to a limiting value of $2\pi f/c$ (light traveling tangentially parallel to the surface). The light line indicated on Fig. 4 represents this latter condition.

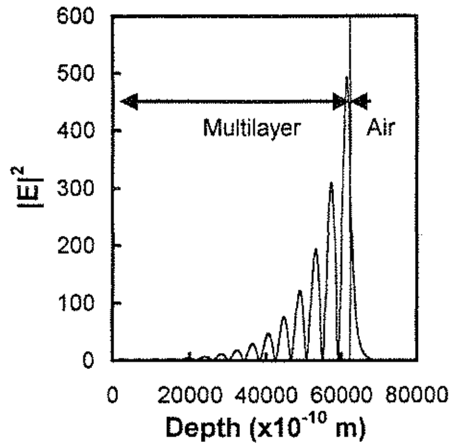
A similar, but considerably more involved, calculation must be done to describe propagation in the PBG material. The theoretical formalism developed in reference [1] was used to divide the dispersion diagram into radiative and nonradiative zones for propagation within the multilayer. Diagonal hatching indicates the radiative regions within the multilayer of the dispersion diagram. Note that for zero parallel wave vector, corresponding to light at normal incidence, there is a nonradiative zone from frequencies 19×10^{13} to 24×10^{13} Hz. This region corresponds to the normal incidence PBG of the multilayer centered at a wavelength of 1.39 μm (21.5×10^{13} Hz). At angles away from normal incidence, the bandgap moves to higher frequencies as expected such that, at the wave vector values used in our experiment, the bandgap encompasses the range of our tunable laser.

The surface modes exist in the unhatched regions of the dispersion diagram; that is, the surface modes cannot radiate either into the air or into the multilayer. Ramos-Mendieta *et al.* [2], [3] have explored the behavior of the surface modes in dielectric multilayers as a function of termination. In simple terms, their results predict that the surface mode dispersion moves through the bandgap from one band edge to the other as the termination is varied. This behavior is mirrored in the experimental dispersion plotted as the squares and circles on the dispersion curve in Fig. 4. The squares correspond to the data taken in the Kretschmann configuration with the fully terminated sample, and the circles correspond to the half-layer terminated sample measured in the Otto configuration. The latter modes appear on the dispersion diagram near to the middle of the bandgap, whereas the former occur close to the upper band edge (but within the nonradiative zone) in qualitative agreement with previous theory.

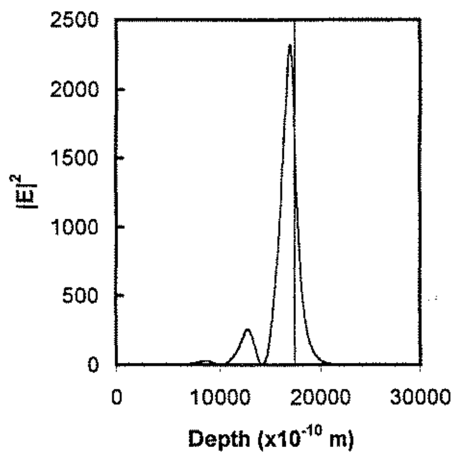
V. Surface Mode EM-Field Calculations

A second facet that differentiates the nature of the surface modes on samples with different terminations is the very different degrees of localization of the modes at the surface. For the mode that occurs near midgap, the attenuation of the PBG is near its maximum and the mode should be tightly confined to the surface. In contrast, the mode at the zone edge exists just within the forbidden gap, where the attenuation is not as strong, and thus the evanescent field can penetrate much further into the multilayer. The difference in localization has a profound effect on the magnitude of the EM field enhancement that occurs within the last layer when the surface mode is excited. Large field enhancements are desirable for applications such as surface nonlinear optics, sensors, and atom mirrors. Furthermore, the difference in localization has a significant effect on the choice of sample parameters in designing a multilayer for use in a Kretschmann configuration. As detailed above, the Kretschmann geometry in which the PBG is physically contacted to the prism is much more desirable for SEW applications.

For the 1-D samples, it is relatively straightforward to theoretically predict the reflectivity of the prism/multilayer configurations using Fresnel's equations. In general, these calculations correspond fairly closely with the experiment,



(a)



(b)

Fig. 5. Calculated profiles for $|E|^2$ normalized to an incident $|E|^2 = 1$ in the prism. The plots are as a function of depth within the multilayer. The vertical line in each plot signifies the PBG-air interface. (a) Full-layer terminated sample consisting of 15 bilayers of TiO_2/SiO_2. (b) Half-layer terminated sample consisting of four bilayers of TiO_2/SiO_2 with a final half-layer of TiO_2.

at least within the fabrication uncertainty of real samples. At the angles at which the reflectivity dips occur, the field profile—the squared magnitude of the electric field $|E|^2$—of the sample can be similarly evaluated to ascertain the nature of the localization and the degree of surface field enhancement. The field calculation is performed by solving for the Fresnel reflection coefficients (including multiple reflection) at each interface within the multilayer. The field amplitudes of the forward and backward propagating waves can then be vectorially added at a number of discrete points within each layer to determine $|E|^2$ as a function of depth within the multilayer sample. The incident field in the prism is assumed to have amplitude $E = 1$.

Calculations of the field profiles for the two modes explored in the samples used in these experiments are presented in Fig. 5. In each calculation it was assumed that the sample was configured in the Kretschmann configuration. The dielectric constants of SiO_2 and TiO_2 were taken to be 2.074 and 4.41, respectively. Dielectric loss roughly corresponding to the intrinsic loss of the materials was accounted for by assigning an imaginary part of 0.0002i to the dielectric constant. The number of bilayers of the multilayer was chosen to optimize the depth of the reflectivity dip. For the full-layer termination, this number corresponded to 15 bilayers, whereas for the half-layer terminated sample, the number of bilayers was four. The field profile was then calculated assuming light incident at the resonant coupling angle through the prism. The squared E-field is normalized to an incident field $|E|^2 = 1$ in the prism. Fig. 5(a) shows $|E|^2$ as a function of depth through the full-layer terminated multilayer sample. The vertical line at about 6.2 μm indicates the position of the air/multilayer interface. The field enhancement reaches a maximum value of 500 in the last layer next to the surface. The field oscillates many times throughout the multilayer array. In contrast, for the half-layer terminated sample, the field rises to a maximum enhancement of over 2000, and there is relatively little oscillation of the field before it comes to a maximum. Again, the vertical line at 1.75 μm indicates the position of the interface between the multilayer and the air. The behavior of the calculated field profiles can be understood in terms of the fact that near the band edge, the attenuation is weaker compared to that for the mode at the band center. Stronger attenuation by the PBG array leads to tighter confinement of the mode to the surface, resulting in a larger field enhancement.

VI. Conclusion

In conclusion, we have experimentally demonstrated the effect of surface termination on the dispersion of surface waves at the interface of 1-D PBG crystals. The essential physics seen in the 1-D samples should mirror the behavior of higher dimensional samples. From a practical point of view, the 1-D PBG samples can serve as replacements for metal films or other surface-active media in many applications that make use of SEW's. The low loss of the PBG materials leads to higher surface field enhancements and narrower reflectivity resonances, properties that are desirable for sensor and nonlinear optic applications. Furthermore, the frequency range of the bandgap, and hence of surface waves, can be engineered by appropriately selecting the periodicity of multilayer dielectric films and their surface termination. Last, the 1-D samples are amenable to straightforward theoretical analysis using Fresnel's equations.

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