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Surface plasmon-like sensor based on surface electromagnetic waves in a photonic band-gap material

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Abstract

The design and operating principles of a new type of surface electromagnetic wave sensor are described and demonstrated. The method of operation of this device is similar to surface plasmon sensors except that the surface-active material—a metal film in the case of surface plasmon sensors—is replaced by a one-dimensional photonic band-gap array. The advantages of using a photonic band-gap material instead of a metal film include enhanced sensitivity, physical, and chemical robustness, and the ability to engineer the optical response of the surface active layer to create a device that operates at any optical wavelength. Experimental results are presented that illustrate sensing action by measuring the shift in the surface mode coupling angle with surface loading.

Keywords: Surface plasmon; Biosensor; Photonic band-gap materials

1. Introduction

In this paper, we demonstrate the principle of operation of a new type of surface electromagnetic wave sensor, similar in operation to a surface plasmon sensor, but which makes use of a one-dimensional photonic band-gap (PBG) material in place of the metal film. The use of PBG materials offers three significant advantages in the operation of surface electromagnetic wave sensors. First, low dielectric loss PBG materials result in sensors with higher surface sensitivity than surface plasmon sensors based on metal films. Second, PBG material properties can be designed and engineered to operate at any optical wavelength. Finally, with an appropriate choice of constituents, the PBG films are mechanically and chemically robust offering the possibility of new environments and applications for this class of sensor.

Surface plasmon (SP) resonance is the basis of a wide selection of commercial and research sensing technologies for the detection of biological and chemical species [1–4]. A SP oscillation is a propagating collective excitation of the surface electrons in a metal. By the use of an appropriate prism configuration [5,6], light can couple to the normally non-radiative SP oscillation. Optical coupling to SP's is manifested by a sharp drop in the reflectivity when monochromatic light is incident at the correct phase matching angle. The phase matching condition for coupling of light to the SP's is highly sensitive to the physical environment at the metal film surface. Small changes in refractive index of the boundary medium or in the dielectric loading of the metal surface lead to a shift in the optimum coupling angle. It is the change in the reflectivity profile that is the physical basis for SP sensing [7–9].

The condition for a material to support surface electromagnetic waves, such as surface plasmons, at its boundaries is that the real part of the dielectric function be less than minus one [10]. This condition is satisfied for a wide variety of metals over frequency intervals in the infrared and visible. However, only a few of these metals exhibit a sufficiently sharp SP resonance to be of use for sensing applications. Another important parameter for selecting a material suitable for use in SP sensors is the dielectric loss. Small dielectric loss indicates small absorption, a condition that is

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necessary to achieve sharp, well-defined SP resonance. The loss-parameter eliminates many materials entirely from use in practical SP sensors and restricts the operating wavelength range of others. The most common materials that exhibit a well-defined SP resonance are silver, gold, copper, and aluminum [11]. Silver is by far the best in principle because it has very low loss; however, it is impractical for real sensors because its chemical reactivity results in poor long-term stability [12]. Gold is the most common compromise material for SP sensors because it is chemically stable. However, gold exhibits a broad SP resonance, it is mechanically soft, and its operating range is restricted to wavelengths in the red and infrared. These material limitations on surface wave sensors can be eliminated by the substitution of a PBG material in place of the metal film.

2. Photonic band-gap materials

Photonic band-gap materials are periodic composites that can be engineered to exhibit metal-like optical properties over given frequency intervals [13]. A PBG material is composed of two constituents with different dielectric constants arranged with a regular periodicity in one, two, or three dimensions. The coherent effects of scattering and interference result in a dramatic modification of the dispersion relation for light traveling in the composite, including the appearance of so-called photonic band-gaps—frequency intervals in which the propagation of light is forbidden. In the photonic band-gap regions the PBG material has metal-like behavior and the optical response of the composite can be described by an effective dielectric constant with a negative real value. It is this negative effective dielectric constant that permits the material to support surface electromagnetic waves at frequencies within the forbidden transmission band.

One advantage of using a PBG material as a surface active medium is that, by an appropriate choice of constituent materials and periodicity, this metallic behavior can be engineered to occur at any desired wavelength. However, it is the low dielectric loss that makes these materials dramatically better for surface wave applications. The dielectric loss of the material is set by the intrinsic loss of the two constituents of the PBG composite. If the two materials are non-metals, the resulting dielectric loss of the PBG composite is orders of magnitude lower than even the lowest loss metal.

The low dielectric loss results in surface mode resonances that are much narrower than surface plasmon resonances in even the lowest loss metals. In general, narrow resonances lead to greater sensitivity and resolution in practical surface wave sensors [12]. The full question of sensitivity for surface plasmon sensing is complicated and much studied. The ultimate sensitivity of any surface wave resonance sensor is determined both by the sharpness of the resonance and the shift in angular position with dielectric loading or refractive index. For the multilayer design used in the experiments described here, the theoretical sensitivity, using a differential reflectance metric from reference [14], indicates a reflectance–change sensitivity for the multilayer of 0.5 nm^{-1} compared to 0.05 nm^{-1} for gold. However, it should be noted that the sensitivity itself could be manipulated in the design of the multilayer. The shift of the resonance position and the resonance width are a function of the number of multilayers, their index contrast, and the location of the surface mode with respect to the center of the forbidden band-gap.

The ability of PBG materials with two- and three-dimensional periodicity to support surface modes has been described theoretically and experimentally in the early days of work on PBGs [15,16]. In the work presented here, we make use of one-dimensional PBG systems consisting of alternating high and low refractive index dielectric multilayers, because they are easy to model theoretically and because they can be commercially manufactured with high precision. In earlier papers the theoretical and experimental analysis of surface modes in these one-dimensional systems has been detailed [17,18]. Here, we demonstrate their potential utility as sensors.

3. One-dimensional photonic band-gap multilayer design

The surface mode dispersion relation in one-dimensional PBGs depends on four parameters: the refractive indices of the two dielectric constituents; the scale of the periodicity; the angular range of operation; and the termination layer thickness [15,16]. By suitably selecting these parameters, it is possible to design a PBG multilayer that exhibits a surface wave resonance at any target wavelength.

The theoretical system modeled consists of a prism/multilayer/air configuration as shown schematically in Fig. 1. This arrangement is essentially a Kretschmann configuration [6] familiar in SP experiments but with a multilayer replacing the metal film. The reflection and transmission of electromagnetic waves from a multilayer sample can be accurately calculated using an iterative implementation of Fresnel's equations [19]. Our program, written in MATLAB, gives a theoretical representation of the reflectivity as a function of incident angle in the prism, θ. At incident angles greater than that for total-internal reflection, dips in the reflectivity represent the coupling of light either to surface modes or to guided modes in the multilayer. The guided versus surface wave modes can be distinguished by their very different sensitivity to changes at the multilayer-air surface and by their distinctive field profiles as a function of cross-section through the multilayer [17,18].

For the experiments described here, TiO_2 and SiO_2 were chosen for the high and low refractive index materials, respectively. These materials are very robust and easily amenable to accurate fabrication by commercial thin film labs. The dielectric constants for TiO_2 and SiO_2 supplied by the thin film fabrication company [20] are 4.84 and 2.13, respectively at

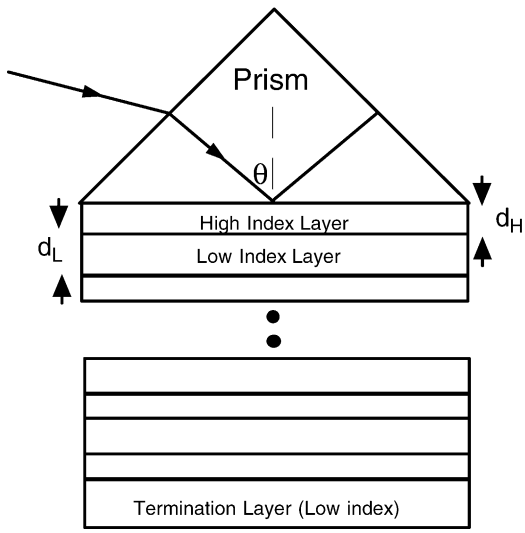

Fig. 1. Schematic representation of the prism and multilayer system modeled theoretically. The alternating high and low refractive index layers have thickness values determined from Eq. (2) except for the termination layer whose thickness is adjusted to set the surface mode at an experimentally favorable position.

our target wavelength of 632.8 nm. The dielectric loss was accounted for by adding an imaginary part to each dielectric constant. These loss values are more difficult to find in the literature but were estimated based on a number of sources as 0.0007i for TiO_2 and 0.0001i for SiO_2.

Fig. 1 illustrates a one-dimensional PBG consists of a repeating multilayer of alternating high and low refractive index layers. For applications such as optical filters, in which the light propagates normal to the layers, the design condition to achieve a forbidden transmission band centered at a wavelength, λ, is that the high and low index layer thickness (d_H and d_L, respectively) are given by

$$d_L = \frac{\lambda}{4n_L}, \qquad d_H = \frac{\lambda}{4n_H}$$

where n_H and n_L are the high and low refractive indices, respectively. Such a configuration is known as a quarter-wave stack or Bragg reflector. In the surface wave application described here, we require a forbidden transmission band for angles of incidence of light above that for total-internal-reflection in the coupling prism. As the angle of incidence of light is varied away from normal incidence, the position of the band-gap of a one-dimensional photonic band-gap material shifts to shorter wavelengths. In this case, the modified angle-dependent design condition is given by

$$d_H = \frac{\lambda}{4n_H \cos\theta_H}$$

$$d_L = \frac{\lambda}{4n_L \cos\theta_L}$$

where θ_H and θ_L are the propagation angles of the light within the high index and low index layers, respectively. Using these relationships, the initial thickness values of the TiO_2 and SiO_2 layers were calculated using our target wavelength value of 632.8 nm, the refractive indices of the constituent materials, and a target band-gap at angles in the vicinity of the prism total internal reflection angle of 42°.

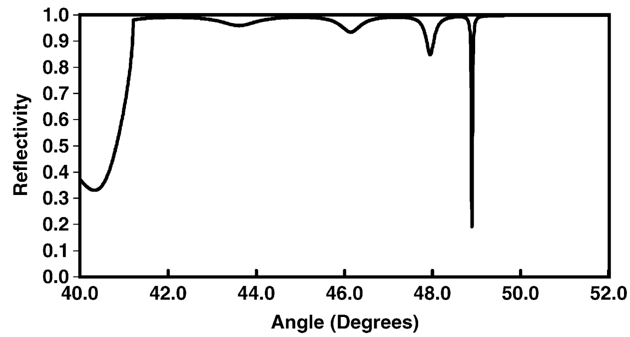

Fig. 2. Reflectivity profile of the multilayer design calculated using an iterative implementation of Fresnel's equations.

The number of bilayers as well as the termination layer thickness determines the angle at which the surface wave is seen and the depth and angular width of the reflectivity dip. Achieving a good surface wave resonance for sensing applications requires a balance between angular width that is broad enough to be compatible with the angular divergence of the laser, and a reflectivity dip close to zero so as to clearly measure a shift when an additional thickness is added to the multilayer. The number of bilayers and the termination layer thickness were adjusted iteratively until the numerically calculated reflectivity versus angle plots indicated a surface mode resonance that was promising for sensing applications. Fig. 2 shows a plot of the numerically calculated reflectivity versus angle (in degrees) for the final multilayer design. This final design consisted of 13 complete bilayers of TiO_2/SiO_2 with layers thicknesses of 117.3 nm and 182.4 nm, respectively, and a final termination pair of 117.3 nm TiO_2 and 156.5 nm SiO_2.

4. Experimental configuration and results

To quantify the accuracy of the design process and to demonstrate the sensitivity of the PBG surface mode as a sensing method, we made a series of angular reflectivity measurements using the experimental setup represented schematically in Fig. 3. A Helium-neon laser beam with a wavelength of 632.8 nm was mechanically chopped before being directed through the prism onto the multilayer. The polarizer was oriented so that the incident light was s-polarized on the multilayer. A computer controlled rotation stage varied the angle of incidence of the laser beam by rotating the prism. A second rotation stage synchronously moved the detector so that it always intercepted the reflected beam. The reflected light was incident on a photocell whose output signal was fed to a lock-in amplifier. A data acquisition card in the computer digitized the analog output signal from the lock-in amplifier. In the experiments described here, the incident angle of the

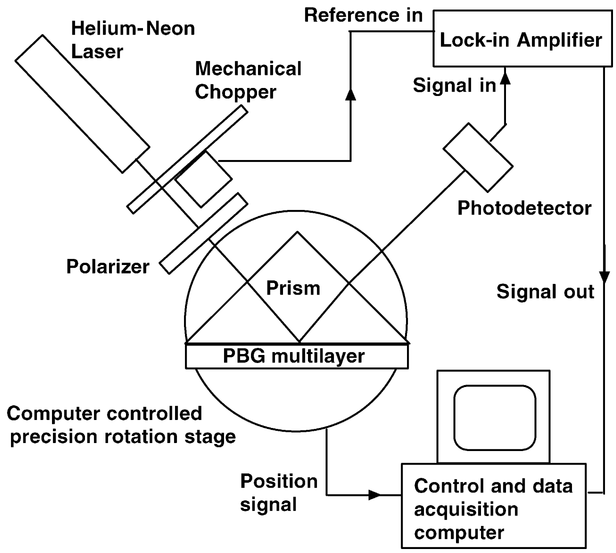

Fig. 3. Schematic representation of the experimental configuration used to measure reflectivity profile.

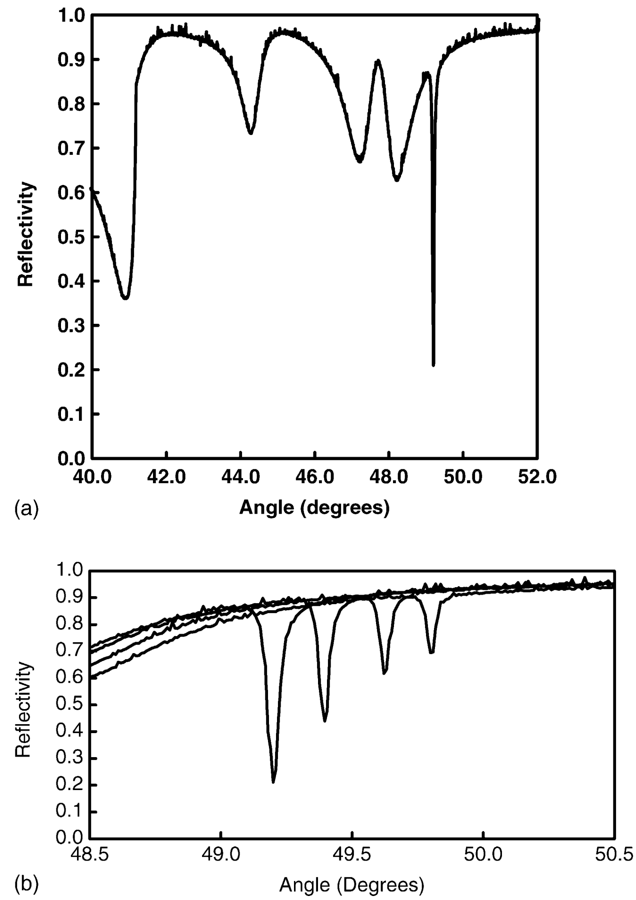

Fig. 4. (a) Experimentally measured reflectivity for the bare TiO_2/SiO_2 multilayer. (b) Reflectivity profile illustrating the shift of the surface mode with surface loading. Leftmost dip corresponds to the bare multilayer surface; the next three dips correspond to multilayer with cryolite adlayers of 5.0 nm, 7.3 nm, and 3.5 nm, respectively.

laser light was varied over the range of 30–60°, which corresponded to an angular range for θ of 35–55° at the prism multilayer interface. A data acquisition program written in LabVIEW controlled the process of initiating and synchronizing the motion of the rotation stages and of acquiring the reflectivity signal from the lock-in amplifier.

The first reflectivity plot shown in Fig. 4(a) is of the bare multilayer with the TiO_2/SiO_2 layers described above. For comparison Fig. 2 shows the predicted results from the theoretical design program. The agreement between the theoretically predicted and the experimentally measured reflectivity is generally good. Total-internal reflection (TIR) occurs at an angle of 41.2°. The first three broad reflectivity dips at higher angles than TIR correspond to coupling of the laser light to bulk guided modes within the entire multilayer. These guided modes are more pronounced in the experimental results than in the theory. Part of the explanation for this observation is that the theory calculation is based on an infinite plane wave, whereas in the experiment more energy can be lost to the guided modes as they carry energy away from the finite spot size. The very narrow reflectivity dip at the largest angle corresponds to the surface mode. All of the modes (guided and surface) in the experimental data appear to be at a slightly higher angle than predicted by theory. This effect could result from slight variation between the specified and fabricated layer thickness values.

This angle at which coupling to the surface mode occurs is predicted to increase if any additional material is added to load the surface of the multilayer. To verify this surface mode sensitivity, a sequence of experimental tests was preformed by adding successive layers of cryolite to the PBG multilayer by vacuum deposition. Cryolite has a refractive index of 1.35 and it was chosen because it is a dielectric material that is amenable to vacuum deposition. Three successive layers of cryolite were added in thickness values of 5.0 nm, 7.3 nm, and 3.5 nm as measured by the crystal thickness monitor in the vacuum deposition system. After each layer was added the PBG multilayer was returned to the prism configuration and a reflectivity spectrum measured.

Fig. 4(b) shows the reflectivity plots for the bare multilayer and for the three successive layers of added cryolite. Note that the angular range in this plot is over a narrow region in the vicinity of the surface mode. The angular shift of the surface wave mode with surface loading is clearly visible as the successive reflectivity dips are completely separated from one another. The shift values are consistent with those calculated theoretically within the ±20% uncertainty of the crystal thickness monitor. The reflectivity dip becomes less deep with the addition of successive adlayers. This effect is possibly due to the fact that with additional thickness at the termination layer the surface mode is being pushed closer to the middle of the forbidden band-gap where it becomes more tightly confined to the surface and hence couples less strongly to the incident light from the prism. Designing a multilayer with a surface mode closer to the band edge can ameliorate this condition.

5. Conclusion

The experimental results illustrate the ability of a one-dimensional photonic band-gap material to be configured as a surface electromagnetic wave sensor. The use of PBG materials as replacements for the metal films in surface-plasmon sensors offers numerous potential advantages: enhanced sensitivity because of the low material losses, robust films that can be cleaned or used in more aggressive sensing environments, and flexibility in that a PBG material can be designed to work at any desired wavelength. The technology to make PBG-based sensors is readily available because the simple one-dimensional multilayer systems described here can be easily and accurately fabricated using current commercial thin film fabrication technology.

Because of the ubiquity of surface plasmon sensors based on gold films there are a wealth of well-developed immobilization chemistries based on thiol coupling. However, similar methods exist for immobilization to SiO_2-based waveguide and fiber sensors and these methods could be adapted for use on the photonic band-gap materials of the type presented here. Finally, the PBG system can be configured to make sensors that do not necessarily conform to the surface plasmon model. One approach is to integrate sensing action into the PBG itself by modifying the termination layer in which the surface mode is strongly confined. This layer can be made of a different dielectric than the constituents of the photonic band-gap multilayer itself. Thus, for example, gas sensing could be accomplished by having a permeable gas sensitive polymer as the termination layer.

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