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Wavelength-dependent frustrated internal reflection via photonic interface states

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Conventional frustrated internal reflection in which light is able to tunnel across a small air gap between two prisms is a well known phenomenon. In this work, an experimental proof-of-concept demonstration of a polarization and highly wavelength selective version of a similar effect via photonic interface states is given. The photonic interface states are designed to exist within the photonic band gap of Bragg reflectors on the surfaces of the two prisms. © *2011 American Institute of Physics*. [doi:10.1063/1.3660266]

Frustrated internal reflection (FIR), also known as optical tunnelling[1,2] in which light is able to pass through a small air gap between two prisms above the critical angle, has been of interest since the time of Newton and continues to be a topic of interest for potential practical applications.[3] Recently, a theoretical suggestion concerning a distinctly wavelength and polarization dependent extension of this effect has been presented.[4] In this case, each of the two prisms has a nominally identical multilayer Bragg reflector (BR) coated onto its hypotenuse. The associated transmission, which can be significant across an air gap much larger than that in conventional FIR, is via coupling between a pair of evanescent photonic interface states, one at the surface of each prism, in the form of symmetric and anti-symmetric combinations. These are predicted to lead to transmission peaks at two wavelengths determined by the strength of the interaction between the coupled states, which in turn depends upon the size of the air gap and the details of the multilayer structure. The photonic states are confined near the prism surfaces because, (1) they are evanescent in the air in the gap between the two prisms due to total internal reflection above the critical angle and (2) they decay into the coated prisms due to the photonic band gap (PBG) of the BR. The design of the BR, and in particular the thickness of its final overlayer, can be arranged to position the energy of the interface states as desired[5] preferably near the center of the PBG. The general design approach has been used previously in the theoretical and experimental study of Tamm plasmon polaritons.[6–8] The properties of the system, although only a single cavity is involved, are similar to those of a more conventional dual cavity semiconductor structure.[9] We employ a BR designed to allow the transmission of light of wavelength near 1550 nm and TM polarization (magnetic field parallel to the prism surfaces) to give an experimental demonstration of the concept. In principle, such structures could be utilized for a variety of practical uses including filters, sensors, and terahertz frequency generation.[4]

The experiments were carried out using a pair of fairly standard right-angle prisms.[10] They were sputter-coated on the hypotenuse by a commercial company.[11] with a 17 bilayer ZrO_2/SiO_2 structure followed by a final, thicker, ZrO_2 layer. Although materials with a larger refractive index contrast ratio should produce narrower transmission features or require fewer layers to achieve a given transmission linewidth, the ZrO_2/SiO_2 system is a robust and readily available cost-effective alternative and is adequate to demonstrate the proposed effect. We employ a tuneable (1520-1570 nm) diode laser and the basic configuration shown in Fig. 1. The refractive indices of the sputtered ZrO_2 and SiO_2 are effectively real and constant with values of 2.05 and 1.44, respectively, (company[11] data) in the wavelength regime employed. The prisms have a refractive index of 1.5 and hence the critical angle for the system is 41.8°. The nominal design thicknesses for the ZrO_2/SiO_2 BR bilayers were 247/351 nm, respectively. Measurements made on a glass slide coated at the same time as the prisms indicate that, at normal incidence, the PBG side-peaks occur at 1800 and 2340 nm, in good agreement with calculated values of 1800 and 2320 nm. To vary the size of the air gap between the prisms, we used a simple wedge arrangement, as indicated in Fig. 1, in which a thin Mylar™ sheet was inserted between the prisms. A similar approach has been employed by Castro and others when performing the more conventional FIR experiments with uncoated prisms.[12,13] The wedge introduces a small misalignment of the two prisms of ≈0.02° but this is smaller than the quoted 0.05° fabrication tolerance of the prisms and other experimental errors and can be neglected. The laser beam diameter is about 1.5 mm but the measurements are taken using a line-scan facility on the camera for an ≈10% slice of this width and the consequent air gap spread of <100 nm can be neglected as it only contributes a small additional broadening of the transmission features for the accessible range of air gap.

To place the following experimental results in context, Fig. 2 shows the calculated transmission through a symmetric 69 layer SiO_2/ZrO_2 PBG structure (omitting the central air gap and replacing the dual, thicker ZrO_2 layers with a single 247 nm wide ZrO_2 layer) at angle $\theta_i = 45.6664°$ ($\theta_e = 46°$). All calculations employ a standard transfer matrix approach.[14] A PBG region centred near 1550 nm is clearly visible. Also shown are results for coated prisms with a 2.3 μm air gap and final 372 nm wide ZrO_2 layer. In this latter case, transmission is suppressed over a broad range, with the only strong transmission being via the interface states.

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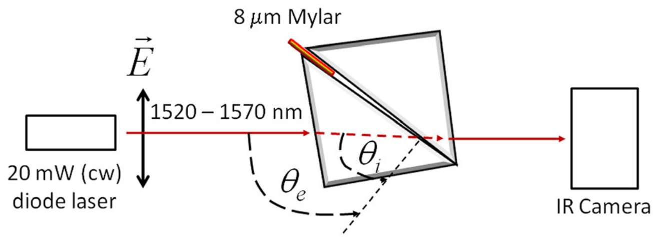

FIG. 1. (Color online) Schematic diagram showing the two coupled prism arrangement and positioning of the Mylar[TM] sheet creating the wedge-shaped air gap. The clamps used to hold the prisms are not shown. The input laser beam is polarized in the plane of incidence (TM). The external and internal angles with respect to the normal to the prism hypotenuse, θ_e and θ_i, respectively are shown; the latter, allowing for refraction at the front prism surface, is used for the theoretical calculations. The output image of the beam is collected by a line-scan infra-red camera and the analogue voltage signal from the full line-scan sent to a digital multimeter.

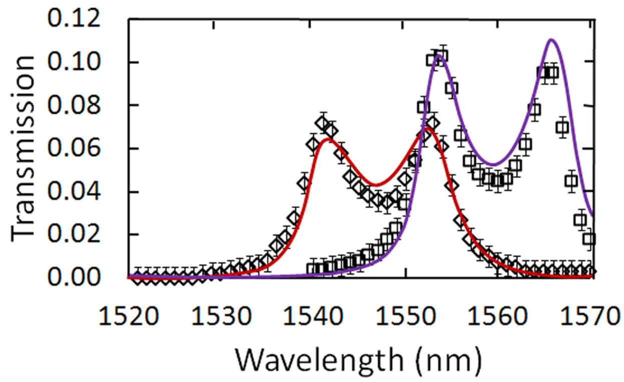

FIG. 3. (Color online) Experimental transmission spectra shown on a common, but arbitrary, scale at external angles $\theta_e = 46^\circ \pm 0.3^\circ$ (open squares) and $\theta_e = 46.5^\circ \pm 0.3^\circ$ (open diamonds). Overall, these results have been scaled to match the absolute transmission of the theoretical plots shown by the solid lines which employ angles corresponding to $\theta_e = 46^\circ$ and $\theta_e = 46.68^\circ$, a gap of 2.4 μm and final ZrO_2 layer thicknesses of 362.5 and 381.5 nm.

For this system, an air gap of about 2.3 μm represents an important reference point. With a smaller gap, the interaction between the interface states is strong enough to produce two increasingly separated 100% transmission features corresponding to symmetric and anti-symmetric interface state combinations. For larger air gaps, the interaction weakens and the single, merged, central transmission feature progressively drops below 100%.

The design of the multilayer coating on the prisms was chosen in order that the transmission features should ideally fall within the narrow tuning range of the laser employed with light at normal incidence to the entry surface of the first prism, with $\theta_e = \theta_i = 45^\circ$. However, the position of the features is particularly sensitive to the thickness of the final ZrO_2 layer. Calculations indicate that they shift by ≈0.5 nm for a 1 nm change in final layer thickness. This can be compensated for by adjusting the angle of incidence, as can be seen in Fig. 3 where we show the experimental TM polarized transmission through the system as a function of wavelength at two slightly different angles and compare these with those of numerical simulations (corrected for refraction at the initial prism interface). The two sets of results can be brought into good agreement by employing different final ZrO_2 layer widths of 362.5 and 381.5 nm on the two prisms and an air gap of 2.4 μm, which is consistent with the experimental estimate of the gap size. Increasing the air gap reduces the transmission but does not noticeably reduce the separation of the two features. Ideally, the final ZrO_2 layer widths should be the same as the prisms were coated at the same time within the sputtering chamber, but given the inherent surface variations in the prisms and details of the coating process some difference is to be expected. With an air gap of 2.4 μm, the interaction between the photonic surface states is relatively weak and should result in a single transmission peak at an energy and corresponding wavelength determined by the degenerate photonic interface states. Thus, the experimental ≈11 nm minimum separation of the peaks is a direct indication of a final layer thickness difference and a corresponding photonic state energy difference. As predicted by theory, transmission for the orthogonal TE polarized light was observed to be negligible, even at the highest powers available from the laser.

To demonstrate the effect of adjusting the interaction between the interface states, in Fig. 4, we show the

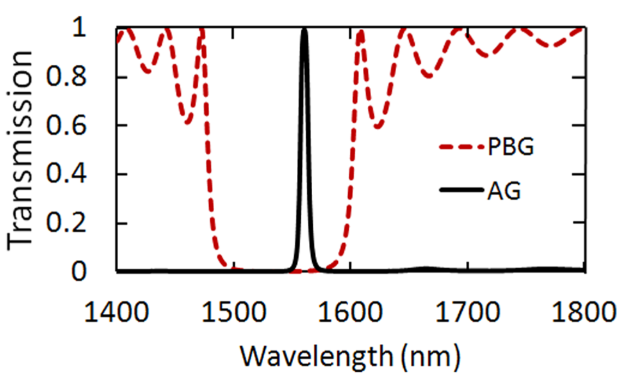

FIG. 2. (Color online) Theoretical plot at $\theta_i = 45.6664^\circ$ ($\theta_e = 46^\circ$) for a PBG structure as described in the text in the absence of an air gap and for coated prisms with an air gap of 2.3 μm (AG). The calculated transmission for uncoated prisms is always less than 0.01 over this range. For the purposes of all calculations, the outer prism surfaces are effectively extended to infinity so there are no losses associated with the exterior air/prism interfaces.

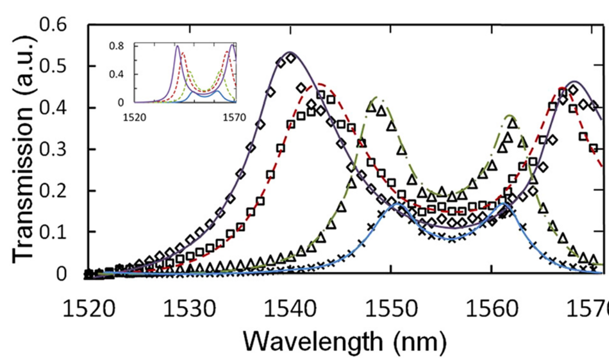

FIG. 4. (Color online) Experimental transmission spectra on a common, but arbitrary, scale at $\theta_e = 46^\circ \pm 0.3^\circ$ as a function of air gap. Error bars are omitted for clarity and the lines are guides for the eye. The solid lines correspond to results for the smallest and largest air gaps with feature separation of about 28 nm and 11 nm, respectively. *Inset*: Theoretical calculation of transmission spectra for air gaps of 1230 nm, 1400 nm, 1750 nm, and 2200 nm using an angle corresponding to $\theta_e = 46.23^\circ$ and final layer widths of 362.5 nm and 381.5 nm.

experimental transmission at $\theta_e = 46 \pm 0.3°$ as a function of air gap. In practice, the size of the minimum air gap which can be obtained and precise experimental knowledge of its value is problematic. It is affected by the quality of the contact between the two prisms, how close the laser beam can be positioned to this region, mechanical strain within the prisms, a slight bevel on the edges of the prisms and the beam diameter. The prisms were clamped quite firmly together to achieve a separation leading to good observed transmission and some deformation of the Mylar^{TM} sheet and/or prisms may have occurred. For the minimum air gap achievable, the maximum separation of the transmission features is ≈28 nm. Simulations employing final ZrO_2 layer widths as above and an internal angle corresponding to $\theta_e = 46.23°$ together with a range of air gaps from 1230 → 2200 nm lead to results which are in generally good agreement in terms of both the form of the transmission and feature separation. The angle chosen for the simulations was fixed by the position of the minimum between the two peaks (≈1555 nm).

In conclusion, we have experimentally demonstrated a form of wavelength-selective frustrated internal reflection via photonic interface/surface states, a different aspect of an age-old, and well understood phenomenon. The good agreement with theory confirms that the experimental observations are due to the proposed mechanism. The results were obtained using relatively inexpensive, commercially sourced coated prisms, and a fairly simple experimental procedure. Such structures have the potential to demonstrate considerably sharper transmission features and benefit from additional associated field enhancement near the interfaces: a 10% increase in refractive index contrast ratio is predicted to decrease line-width by about an order of magnitude and allow the effects to be observed with a significantly larger air gap, much larger than that for which conventional FIR may be observed.[4]

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