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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 in which light is able to pass through a small air gap between two prisms above the critical angle, has been a topic of interest for potential practical applications. Recently, a theoretical suggestion concerning a distinctly wavelength and polarization dependent extension of this effect has been presented. 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 (PGB) of the BR. The design of the BR, and in particular the thickness of its final over-layer, can be arranged to position the energy of the interface states as desired 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. The properties of the system, although only a single cavity is involved, are similar to those of a more conventional dual cavity semiconductor structure. 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.

The experiments were carried out using a pair of fairly standard right-angle prisms. They were sputter-coated on the hypotenuse by a commercial company, with a 17 bilayer ZrO2/SiO2 structure followed by a final, thicker, ZrO2 layer. Although materials with a larger refractive index contrast ratio should produce narrower transmission features or require fewer layers to achieve a given transmission line-width, the ZrO2/SiO2 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 ZrO2 and SiO2 are effectively real and constant with values of 2.05 and 1.44, respectively, (company 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 ZrO2/SiO2 BR bilayers were 247/2340 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 2300 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.

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 SiO2/ZrO2 PBG structure (omitting the central air gap and replacing the dual, thicker ZrO2 layers with a single 247 nm wide ZrO2 layer) at angle θl = 45.664° (θc = 46°). All calculations employ a standard transfer matrix approach. 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 ZrO2 layer. In this latter case, transmission is suppressed over a broad range, with the only strong transmission being via the interface states.
into good agreement by employing different final ZrO$_2$ layer thicknesses. The two sets of results can be brought into agreement by employing different final ZrO$_2$ layer thicknesses. 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 thicknesses 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 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 results are in good agreement with the theoretical predictions. To demonstrate the effect of adjusting the interaction between the interface states, in Fig. 4, we show the 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 ZrO$_2$ layer widths of 362.5 and 381.5 nm.
Experimental transmission at $\theta_e = 46 \pm 0.3^\circ$ 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 sheet and/or prisms may have occurred. For the minimum air gap achievable, the maximum separation of the transmission features is $\approx 28$ nm. Simulations employing final ZrO$_2$ layer widths as above and an internal angle corresponding to $\theta_e = 46.23^\circ$ 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 ($\approx 1555$ 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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$^{10}$We employed Thorlabs N-BK7 PS908L-C prisms which are specified as having a surface flatness of $\lambda/10$ at 633 nm and are anti-reflection coated on the legs to minimize reflection near the 1550 nm wavelength of interest.

$^{11}$Vortex Optical Coatings, Unit 6, Sunnyside Park, Hinckley, Leicestershire, LE10 1TU, UK.

