

Wavelength-dependent frustrated internal reflection via photonic interface states

G. H. Cross and S. Brand^{a)}

Department of Physics, Durham University, South Road, Durham DH1 3LE, UK.

Abstract

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.

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^{a)} Electronic mail: stuart.brand@durham.ac.uk

Frustrated internal reflection (FIR), 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, but recently a theoretical suggestion concerning a more distinctly wavelength and polarization dependent extension of this effect has been presented¹. 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 over-layer, can be arranged to position the energy of the interface states as desired² 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^{3,4,5}. The properties of the system, although only a single cavity is involved, are similar to those of a more conventional dual cavity semiconductor structure⁶. 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 generation¹.

The experiments were carried out using a pair of fairly standard right-angle prisms⁷. They were sputter-coated on the hypotenuse by a commercial company⁸ with a 17 bilayer $\text{ZrO}_2/\text{SiO}_2$ 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 line-width, the $\text{ZrO}_2/\text{SiO}_2$ 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 (company⁸ 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 $\text{ZrO}_2/\text{SiO}_2$ 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 MylarTM 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^{9,10}. The wedge introduces a small misalignment of the two prisms of $\approx 0.02^\circ$ 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 $\approx 10\%$ 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.

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 $\theta_e = \theta_t = 45^\circ$ (see Fig. 1). However, the position of the features is particularly sensitive to the thickness of the final ZrO_2 layer. Calculations, using a standard transfer matrix approach¹¹ and with $\theta_e = 45^\circ$, indicate that the features shift by ≈ 0.5 nm for a similar change in final layer thickness. This can be compensated for by adjusting the angle of incidence, as can be seen in Fig. 2 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 2400 nm, 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 2400 nm 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. 3 we show the 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 ≈ 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 \rightarrow 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 new 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 more than 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 observed¹.

Acknowledgements

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- ⁷ 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.
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Figure Captions

FIG. 1 (Color online) Schematic diagram showing the two coupled prism arrangement and positioning of the Mylar™ 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. 2 (Color online) Experimental transmission spectra 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). Error bars are ± 5 arbitrary units (a.u.) of transmission. Theoretical plots are shown by the solid lines and employ angles corresponding to, $\theta_e = 46^\circ$ and $\theta_e = 46.68^\circ$, a gap of $2.4 \mu\text{m}$ and final ZrO_2 layer thicknesses of 362.5 and 381.5 nm. Although arbitrary transmission units are employed, the relative sizes of the peaks at both angles are as obtained from experiment and theory respectively, thus indicating good agreement between the observed and fitted results.

FIG. 3 (Color online) Experimental transmission spectra at $\theta_e = 46.5^\circ \pm 0.3^\circ$ 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. The data is plotted on a common relative transmission scale and thus show an absolute drop in transmission efficiency with increasing gap. *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.

Figure 1

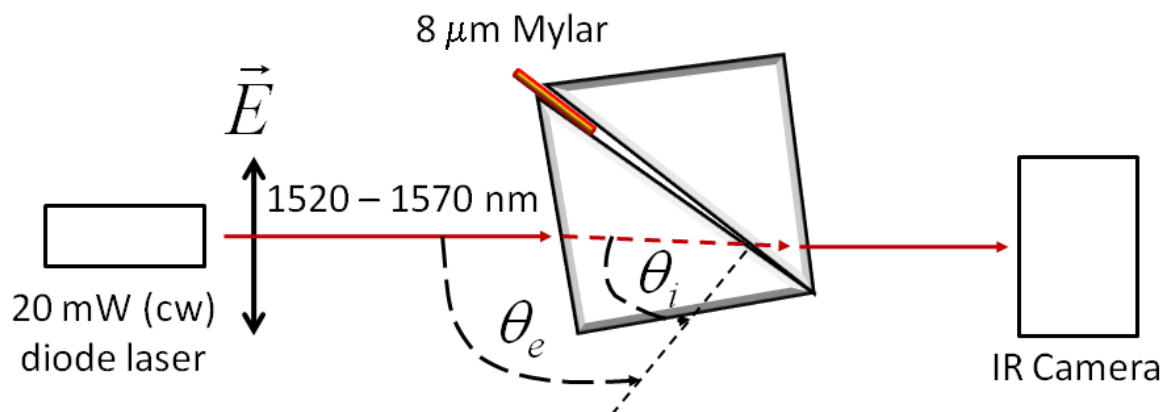


Figure 2

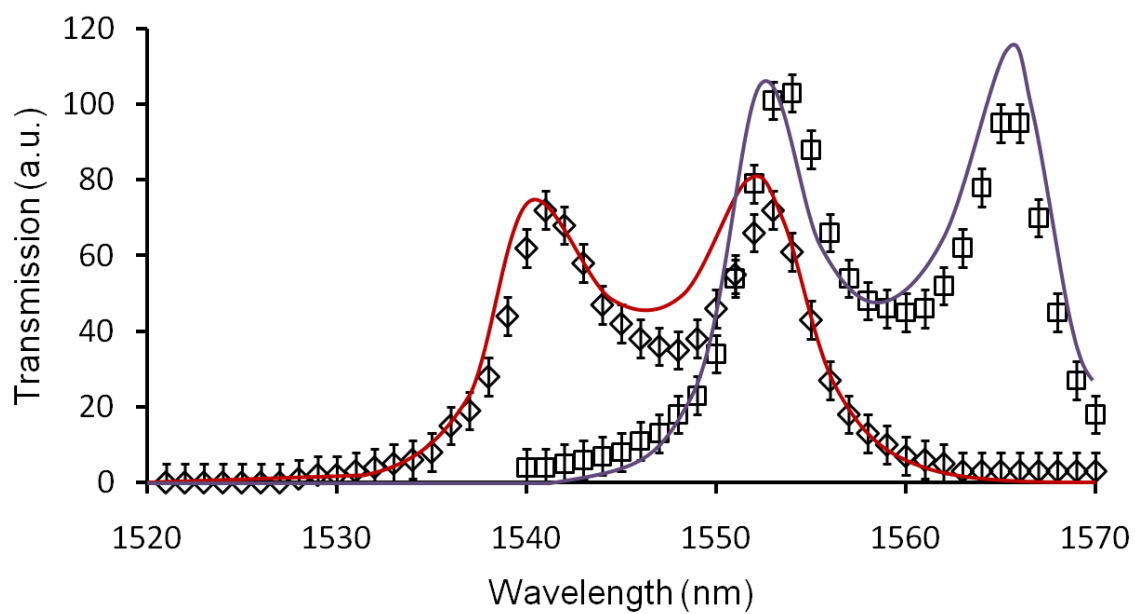


Figure 3

