Evanescently coupled interface states in the gap between two Bragg reflectors

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Interface states are known to exist at the surface of an appropriately structured Bragg reflector. If such reflectors are present on the surfaces of two prisms separated by a narrow gap, the evanescently coupled interface states can interact to produce a pair of very narrow transmission lines, the separation of which can be adjusted by varying the size of the gap between the two prisms. Thus, although only a single cavity is involved, the spectral properties of the system are similar to those of a dual-cavity photonic microstructure. In addition to other potential applications, we propose that such a structure could form the basis of an adjustable beat-frequency emitter in the terahertz regime. © 2010 Optical Society of America

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Some time ago, Yeh *et al.* [1] demonstrated how the transfer matrix method could be applied to the study of electromagnetic surface waves or photonic interface states at the boundary of a multilayer dielectric structure. In the case of a multilayer structure on the surface of a prism, employing a total internal reflection (TIR) configuration, Nelson and Haus [2] discussed, theoretically, how such sharp interface states might be revealed in reflection experiments as a consequence of the associated phase change. In transmission, the use of the evanescent waves associated with a simple dual-prism TIR configuration with an intervening air gap for photographic image processing applications has been described by Bhan and Mehta [3]. In this Letter, we demonstrate how the combination of a dual-prism system overlaid with multilayer dielectric coatings, and the consequent interaction of their coupled interface states, can lead to a structure with a number of potential wavelength selective practical applications.

To demonstrate the nature of the interaction, first consider light incident at an angle of $\theta = 45°$ from a uniform medium with a refractive index of 1.47 through a multilayer structure onto air. Only TM-polarized light is considered, in which the magnetic field, H, is entirely parallel to the interfaces. The multilayer structure consists of 17 pairs of high-/low-index layers, forming a standard Bragg reflector (BR) and a final, somewhat thicker, layer of the high-index material bordering the air gap. The refractive indices of the high- and low-index BR layers are taken to be 2.37 and 1.47 which are representative [4] of the values for TiO_2 and SiO_2, and their respective thicknesses are fixed at 204 nm and 328 nm. The final high-index layer bordering the air gap is taken to have a width of 265 nm. For good-quality materials we are justified in the neglect of absorption as, even with the enhanced field values reported below, the small extinction coefficients in the infrared region [5] mean that there is no significant effect on our results. The structure has been designed using the phase-matching approach described elsewhere [6], in order that the BR has a photonic bandgap centered at 0.8 eV at the incident angle of 45°, with the thickness of the final layer adjusted so as to position the associated photonic interface state at that same energy. As the critical angle for the complete system is 42.9°, no transmission would be expected at the chosen angle of 45°, and, hence, the calculated power reflection coefficient $R = 1$. However, if an identical multilayer structure is positioned at the opposite side of a narrow air gap with the separation being of the order of a few micrometers, as shown in Fig. 1, transmission is possible due to the coupling between the interface states associated with the two structures. The system considered in this Letter is essentially as shown in Fig. 1, except that the prisms are considered as being infinite in extent so that there are effectively no exterior surfaces. We note that there is no significant transmission through the structure in the wavelength range considered for the alternative, TE polarization, for which there are no associated interface states, and thus the structure has an intrinsic polarization-selective functionality.

The transmission coefficient for path T in Fig. 1 has been calculated using a standard transfer matrix approach, and results are shown in Fig. 2 for the case of a 3.5 μm air gap. For comparison, the transmission through a conventional 69-layer BR is also shown, clearly demonstrating a distinctive photonic bandgap region. The effect of the air gap is to give rise to TIR and consequent near-zero transmission over most of the wavelength range shown, but coupling between the

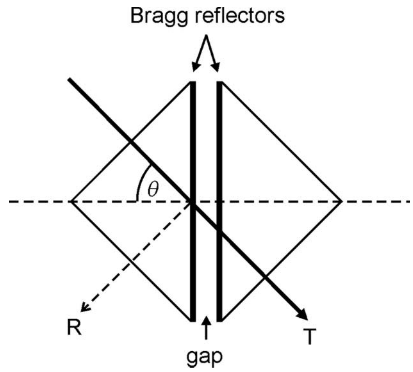

Fig. 1. Basic structure, consisting of two back-to-back prisms with overlaid BRs, separated by a small air gap. For the calculations described, the outer prism surfaces are effectively extended to infinity. For transmission purposes, the light path is in direction T, whereas the reflected light follows path R with $\theta = 45°$.

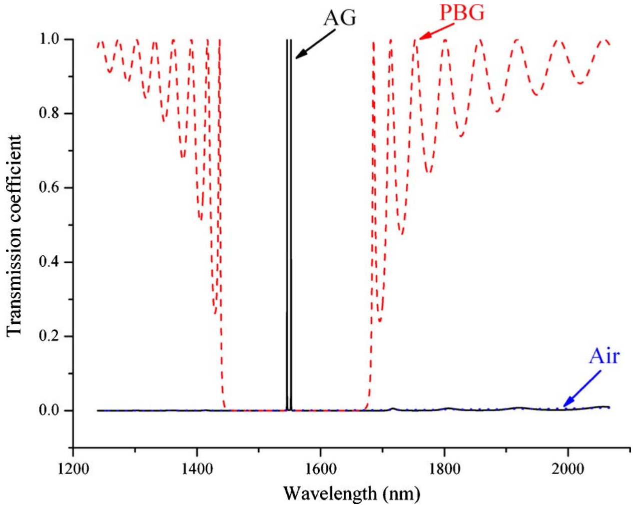

Fig. 2. (Color online) Transmission coefficients for a 69-layer BR with no air gap (PBG); for a full multilayer structure (two 17-layer pair BRs plus thicker final high-index layers and a 3.5 μm air gap) (AG); and for two prisms with a 3.5 μm air gap and no BR (Air)—all for light incident at angle $\theta = 45°$. The air gap causes the structure to behave as an effective total internal reflector over most of the range shown, but the interaction between the evanescent fields of the photonic interface states leads to two distinctive narrow-width transmission lines, which are shown on an expanded wavelength scale in Fig. 3.

interface states results in two sharp peaks in the transmission spectrum. In the absence of the multilayer structures on the surfaces of the two prisms, and their associated interface states, the transmission coefficient is small throughout the range considered, as is apparent in Fig. 2. A more detailed illustration of the transmission coefficient for several different air-gap separation values on an expanded wavelength scale is shown in Fig. 3. As can be seen, the transmission lines are narrow and, in terms of energy, the separation of the line-pairs shown ranges up to about 6 meV with a corresponding frequency of 1.5 THz as the air-gap width is decreased to 3 μm. The average energy of the two transmission peaks is centered at the isolated interface state design value of 0.8 eV, independent of the width of the air gap. In the case of the 3.5 μm air gap, a snapshot in time of the associated H field is shown in Fig. 4 for both the lower and upper energy transmission peaks associated with the features labeled S and A, respectively, in Fig. 3. The plots are characteristic of symmetric and antisymmetric combinations of the isolated interface evanescent states. We note that the associated time-averaged field intensity (H^2) is orders of magnitude higher than that of the incident wave across much of the air gap, and across all of the gap in the symmetric case. If a thin metallic layer is introduced at the interior prism/multilayer interface, it is possible to enhance the field still further, consistent with an observation in our earlier work [7], although this is at the expense of a reduced transmission coefficient.

As the existence of the evanescent states and their energy are dependent upon the material in the gap between the two prisms and the angle of incidence, the separation of the transmission lines can be altered by varying these parameters. In practice, there will be some additional broadening in an actual structure because of natural variations in the BR layer widths, which will depend on the reliability of the BR fabrication process employed, and the use of a smaller number of layers in the BR would also increase the broadening. Use of a structure with a larger refractive index contrast would give rise to a narrowing of the linewidth, or allow a smaller number of layers to be employed but would also involve a change in the prism geometry. We note that in order to maximize transmission, it is essential to maintain the symmetry of the multilayer structures on the surfaces of the two prisms, and this can be most simply achieved in practice by fabricating the two multilayer structures in the same growth run. A relative difference of a few percent in the widths of the two layers adjacent to the air gap gives rise to a noticeable broadening and effectively halves the value of the transmission coefficient. On the other hand,

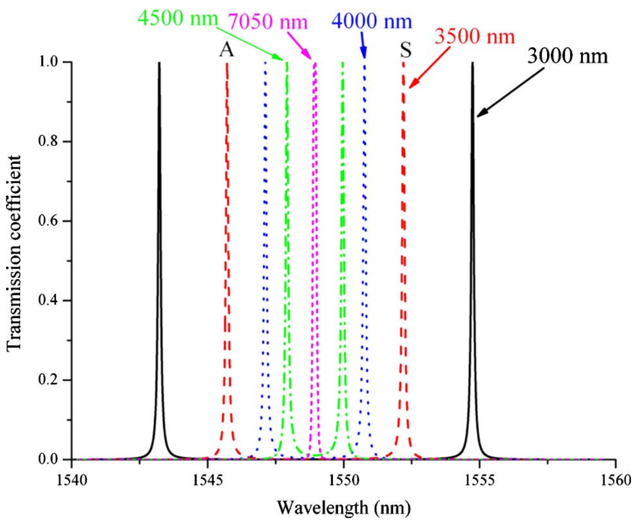

Fig. 3. (Color online) Transmission coefficient as a function of wavelength for a series of different air-gap widths for light incident at angle $\theta = 45°$. In the weak coupling regime with an air gap of 7050 nm, the single effectively flat-top transmission feature has a FWHM of 0.15 nm, whereas there is a FWHM = 0.11 nm for the 3000 nm air gap.

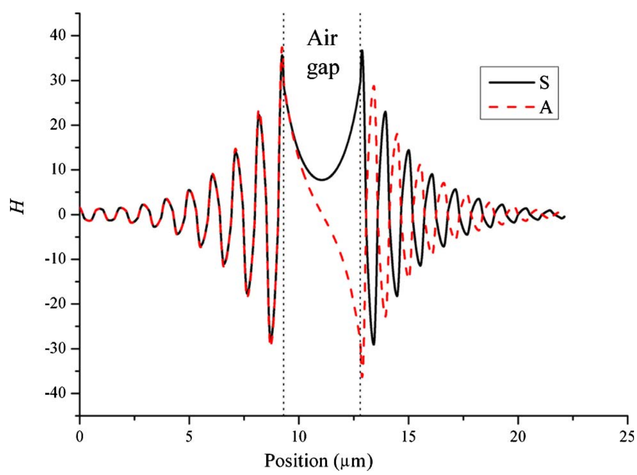

Fig. 4. (Color online) Snapshots in time of the H field associated with the lower-energy (S) and upper-energy (A) transmission lines for the 3.5 μm air-gap structure indicated in Fig. 3. The peaks in $|H|$ near the left and right edges of the air gap are in the high refractive index regions of the multilayer structures. The incident H field has unit amplitude.

because of the exponential envelope of the field profile, variations in layer widths away from the air gap have a decreasing effect. In a practical situation, it should be possible to compensate for a variation of a few percent in the thickness across the final layer by an appropriate adjustment of beam position and the relative position of the two prisms to achieve high transmission. The juxtaposition of the regions on the surface can be altered by moving the prisms parallel to each other without affecting the gap width.

We note that the structure, as described, could be employed to produce an optical flat-topped notch or narrow bandpass filter, depending on whether the reflected or transmitted output is employed. For the current design, this occurs when there is weak coupling between the interface states with an air-gap width of 7050 nm, a scenario illustrated in Fig. 3. A more conventional structure designed to produce such a flat-top transmission feature involving the interaction between states in a pair of microcavities was studied by Beggs *et al.* [8]. The dual-prism structure properties are rather different from those of a conventional normal incidence BR because the rejected frequencies emerge at right angles to the incident and transmitted frequency components rather than being reflected antiparallel to the incident radiation. The structure thus has potential uses as, for example, a component of an otherwise conventional laser system as a means of laser mode control: only those modes compatible with the allowed transmission features of the structure are available to encourage laser action, whereas all other modes are suppressed. With the use of an appropriate photomixer external to the dual-prism structure it may be possible to produce beat-frequency terahertz radiation from the transmitted beam. (See [9–13] for both general accounts and specific examples of the use of the beat-frequency concept for terahertz frequency generation.) In a more ambitious approach, the structure might be employed with nonlinear material placed directly within the multilayer structure or with the material of the prisms comprising the lasing medium. Because of the enhanced field within the gap, a nonlinear material with a relatively modest response, such as that observed in a number of organic materials, could possibly be placed in this region. However, the refractive index within the gap would then be in the region of, say, 1.5. Consequently, higher refractive index prisms and an alternative multilayer structure would be required in order to satisfy the condition for TIR. Clearly these more speculative ideas would require further investigation.

Although a particular combination of multilayer structure and materials has been considered in this work, with corresponding implications for the operational frequency range, the general results are applicable to other systems in which the photonic bandgap and characteristic interface state energies can be readily adjusted and a modified prism refractive index and geometry employed.

References

1. P. Yeh, A. Yariv, and C.-S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).
2. R. L. Nelson and J. W. Haus, Appl. Phys. Lett. **83**, 1089 (2003).
3. C. Bhan and P. C. Mehta, Opt. and Laser Technol. **21**, 44 (1989).
4. H.-Y. Lee and T. Yao, J. Kor. Phys. Soc. **44**, 387 (2004).
5. O. Zabeida, A. Amassian, S. Larouche, C. Lavigne, J. E. Klemberg-Sapieha, and L. Martinu, *Optical Interference Coatings*, OSA Technical Digest Series (Optical Society of America, 2001), paper WA7.
6. S. Brand, R. A. Abram, and M. A. Kaliteevski, J. Phys. D **43**, 145104 (2010).
7. S. Brand, R. A. Abram, and M. A. Kaliteevski, J. Appl. Phys. **106**, 113109 (2009).
8. D. M. Beggs, M. A. Kaliteevski, S. Brand, and R. A. Abram, J. Mod. Optics **51**, 437 (2004).
9. D. Dragoman and M. Dragoman, Prog. Quant. Electron. **28**, 1 (2004).
10. G. K. Kitaeva, Laser Phys. Lett. **5**, 559 (2008).
11. T. Kitada, F. Tanaka, T. Takahashi, K. Morita, and T. Isu, Appl. Phys. Lett. **95**, 111106 (2009).
12. N. Kim, J. Shin, E. Sim, C. W. Lee, D.-S. Yee, M. Y. Jeon, Y. Jang, and K. H. Park, Opt. Express **17**, 13851 (2009).
13. R. Gehlaar, M. Swoboda, M. Sudzius, M. Hoffmann, H. Frob, V. G. Lyssenko, and K. Leo, Appl. Phys. B **86**, 413 (2007).