Gap modes of one-dimensional photonic crystal surface waves

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ABSTRACT

The finite-difference time-domain method is employed for the analysis of coupling of the surface modes of two truncated one-dimensional photonic crystals separated by a gap. Wavevector, field distributions and existence conditions of the coupled surface modes are investigated. The wavevector of symmetric gap modes increases with decreasing gap width, while that of antisymmetric modes decreases - exactly opposite to the situation for surface plasmons on metallic half-spaces separated by a dielectric gap. Photonic crystal gap modes could be easily used as effectively non-dissipating gap mode waveguides.

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In 1987 John [1] and Yablonovitch [2] independently suggested the concept of special dielectric periodic structures (photonic crystals) that can prohibit electromagnetic wave propagation for a range of frequencies [1-4] in any direction. Theoretical and experimental studies have shown that the interface of a truncated dielectric photonic crystal can support surfaces waves [3-20]. Elimination of these surface modes is important for reducing radiation losses of conventional photonic crystal devices whose energy can leak into surface modes if they exist [11,15,17,20]. Also, the study of surface waves on photonic crystals is interesting in its own right for the development of low-loss dielectric surface wave technology such as waveguides and sensors [12], narrow-band filters [19], etc. In this paper photonic crystal surface polariton gap modes formed by coupling of two photonic crystal surface waves separated by a dielectric gap are studied by an exact numerical solution of the Maxwell equations using a finite-difference time-domain (FDTD) method [21]. Photonic crystal surface polariton gap modes maybe of particular interest since there is renewed interest in their metallic analogue (surface plasmon gap modes) that are being investigated for nano-optical waveguiding applications [23]. This is especially the case since surface waves resonances on photonic crystals may be sharper than those on metals due to much lower dissipation [12,13], meaning that photonic crystal surface modes may have comparatively large propagation distances.

Consider two one-dimensional photonic crystals periodic along the y-axis separated by a dielectric gap (Fig. 1). The termination factor, τ, is defined as the fraction of the outermost cell which remains after the superlattice is cut. For example, if τ = 0.75 means that ¼ of the last cell is removed and ¾ remains intact. An FDTD algorithm for the numerical solution of the Maxwell equations in two-dimensions was implemented and boundaries of the computational windows are terminated with a first-order Mur boundary condition [22]. The dimensions of each grid cells are Δx = λvac / 50 and Δy = λvac / 100 in the x and y axes respectively. The pe-
period of the superlattice $d = 0.3\lambda = 30\Delta_y$ (note that the band-gap structure and properties for the infinite photonic crystal with the same parameters as our finite photonic crystals in this paper is given in detail in [3]). Surface wave excitation is by two $E_z$ point sources, one located on the interface of each photonic crystal half-space and at the far left of the computational window – resulting in surface wave excitation on each interface. Same as for plasmons [24], when photonic crystal surface polaritons are coupled both symmetric and antisymmetric combinations are possible, i.e. degeneracy of the separate surface modes is lifted as antisymmetric and symmetric coupled modes with different wavevectors result. For excitation of antisymmetric modes (with respect to the electric field) a phase shift of 180 degrees between the two point sources is introduced. For excitation of symmetric modes the sources are in phase. The incident source is switched on for a time, $t = 5000\Delta_t$, where $\Delta_t = \Delta_y/(2c)$ and $c$ is the speed of light in a vacuum. Computation time for the $300\times500 = 150000$ grid cells for all 5000 time-step iterations is about 10 minutes on a 1.8GHz AMD Athlon XP personal computer. The total electric field, which is given by the $z$ component of the electric field, $E_z$, is presented in Fig. 2 for a superlattice with termination factor $\tau = 0.5$ (surface waves exist for approximately $0.4 < \tau < 0.6$ for this structure).
The period of the superlattices is $d = 0.3\lambda_{vac}$. We consider alternate layers of vacuum, with width $0.8d$ and dielectric permittivity $\varepsilon_{vac} = 1$ (unshaded layers in Fig. 1) and a high-index medium with width $0.2d$ and $\varepsilon_2 = 13$ (shaded layers in Fig. 1). $\tau$ is the termination factor which is considered to be the same for each superlattice. A dielectric gap of width $g$ separates the two photonic crystal half-spaces.

In Fig. 2 a photonic crystal surface polariton gap mode (symmetric electric field case) is propagating along the $x$-axis from the point of excitation (near the left edge of the computational window). The field is exponentially decaying into each superlattice ($y$ direction), being localized within about $3d$ of the interface (Fig.2a) - this is appears to be the maximum localization achievable for any termination factor (and any guided mode in any photonic crystal). As can be clearly seen from Fig. 2b, the amplitude along the direction of propagation is practically non-decaying, and this is our requirement for the mode to be a true eigenmode of the structure. Since such an eigenmode is non-radiative, experimental excitation of such modes should be achieved by end-fire excitation, prism coupling or the methods for excitation of surface plasmons [24] such as attenuated total-reflection. The wave vector of the eigenmode in Fig. 2 appears to be different (greater) to that of mode of the individual surface (or with $g$ much larger than the penetration depth of the surface mode into the vacuum gap). This is to be
expected as the gap width decreases and the two separate modes become coupled, just as for plasmons [24].

**Fig. 2.** (a) and (b) Total electric field distribution for a photonic crystal surface polariton gap mode (symmetric electric field – propagating left to right) with gap width \( g = 0.5d = 0.1\lambda_{\text{vac}} \). The absence of the gap mode observed in the region \( x > 450 \) is due to the mode being excited at the left edge of the window and propagating only a finite distance during the finite time iterations performed. (b) The electric field along a vacuum - photonic crystal interface.
Fig. 3. (a) Dispersion of the wavevector due to varying gap width. Circles represent wavevectors for antisymmetric excitation (with respect to the electric field) while crosses are for symmetric excitation. (b) Dispersion of the wavevector for varying excitation frequency for the symmetric (upper dashed curve) and antisymmetric (lower dashed curve) modes with $g = 0.5d$ (i.e. data points with $g / d = 0.5$ in Fig. 3a). The solid curve is for the symmetric and antisymmetric modes with $g = 2d$.

To quantitatively analyze the dispersion of the wavevector with respect to varying gap width the electric field along a vacuum - photonic crystal interface is expanded into the Fourier integral and the Fourier amplitude is expressed as a function of wave vector. The value of the wave vector at the position of the maximum Fourier amplitude is taken as the wave vector of the gap mode. The dispersion of the wavevector due to varying gap width is presented in Fig. 3a and due to varying excitation frequency in Fig. 3b. For large gap widths (compared to penetration depth) both symmetric and antisymmetric modes (with respect to the electric field) are hardly coupled and the wavevector tends to that of a surface mode on the single truncated photonic crystal (see large gap widths in Fig. 3a, or solid curve in Fig.3b). As gap width decreases the wavevector of antisymmetric modes rapidly decreases (see Fig. 3a and lower dashed curve in Fig. 3b). As mentioned above we have the true eigenmode if the amplitude of the field is non-decaying along the direction of propagation. If the gap width is smaller than $g / d \approx 0.45$ it is not possible to observe an antisymmetric eigenmode in the nu-
merical analysis of the electric field structure. Physically this must be the case since the velocity of the antisymmetric mode would otherwise exceed that of light in a vacuum (as can be seen in Fig. 3a and comparing wave vector to the wavevector in a vacuum $k_{\text{vac}} d \approx 1.88$ (lower dashed curve)). On the other hand the wavevector of the symmetric gap polariton is increasing with decreasing gap width (see Fig. 3a and upper dashed curve in Fig. 3b). However, symmetric gap modes may not exist for arbitrarily small gap widths since the wavevector will eventually be outside of the photonic bandgap or the wavevector of the gap mode will be matched to that of conventional guided modes in the adjacent high-index layers – in this case the field can leak into the periodic structure. Above the upper dashed line in Fig. 3a we also observed no symmetric eigenmodes (corresponding to region $g / d < 0.3$). For example, Fig. 4 for the structure with the gap width $g / d = 0.05$ shows the electric field radiating into the photonic crystal. However, all data points on Fig. 3b corresponded to eigenmodes. The same upper cut-off line in Fig.3a can not be applied to Fig. 3b because of the shifting photonic bandgap. While the photonic bandgap changes with frequency the position of the surface mode wavevector with respect to the bandgap hardly changes (it is known that the dominant variable for shifting the surface mode wavevector with respect to the bandgap is the termination factor [3,7]).
Fig. 4. (a) and (b) Electric field distribution for the gap width $g / d = 0.05 = 0.015 \lambda_{\text{vac}}$ shows the electric field propagating into the photonic crystal half-spaces (a). (b) The electric field along a vacuum - photonic crystal interface. We can see that this is not a true eigenmode of the structure since the amplitude is clearly decaying along the direction of propagation (b).

In conclusion, the finite-difference time-domain method was employed for analysis of coupling of photonic crystal surface modes separated by a dielectric gap – photonic crystal surface polariton gap modes. The wavevector of symmetric (electric field) gap modes increases with decreasing gap width, while that of antisymmetric modes decreases. It is interesting to note that this opposite to the situation for gap modes of plasmons on metallic half-spaces separated by a dielectric gap [24], in which case the wavevector of the antisymmetric mode increases with decreasing gap width (due to attraction of oppositely charged regions in this case). It is important to note that dissipation of photonic crystal surface polariton gap modes can be much smaller than that of gap plasmons as has been shown for conventional photonic
crystal surface modes [12-13]. This is because losses are determined mainly by scattering on
surface roughness rather than dissipation (and surface roughness), which should naturally be
strong in a metal, but not necessarily in the dielectric photonic crystal structure (which can
have practically real dielectric permittivity). Therefore nano-waveguides based on photonic
crystal surface modes and gap modes should have much larger propagation distances than re-
cently proposed nano-waveguides based on plasmons on metallic surfaces. However, it
should be noted that subwavelength localization of the fields is in principle not possible in the
case of conventional dielectric structures (including photonic crystals), while it is possible for
metallic plasmon based waveguides [25]. The affect of surface roughness and nonuniformities
as well as more complex structures, such as bend losses of photonic crystal surface polaritons
gap mode waveguides, application to 2-and 3-dimensional nano-optical circuits, etc., integra-
tion with plasmonic components, etc. are topics for future investigations. This paper demon-
strates the FDTD may be most suitable for such problems which may be difficult or impossi-
ble to consider analytically.
References


