Waveguiding properties of surface states in photonic crystals

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We propose and analyze novel surface-state-based waveguides in bandgap photonic crystals. We discuss surface mode band structure, field localization and effect of imperfections on the waveguiding properties of the surface modes. We demonstrate that surface-state-based waveguides can be used to achieve directional emission out of the waveguide. We also discuss the application of the surface-state-waveguides as efficient light couplers for conventional photonic crystal waveguides.

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Introduction. Photonic crystals (PCs) have attracted increasing attention in the last decade due to their unique properties and possible applications in integrated optical and photonic devices like light emitting diodes, delay lines, waveguides and lasers [1, 2]. Among variety of photonic-crystal-based devices waveguides play a crucial role not only as optical interconnections but also as active elements in wide-angle branches, filters, channel add/drop filters, tapered couplers, optical switches, etc. Waveguides represent line defects in periodic crystal structures supporting guided Bloch modes whose frequency is located in the bandgap. These modes are strongly confined within the waveguide region and can propagate without loss to substantial distances. In the present letter we propose a novel type of waveguiding structures, namely waveguides that operate on surface states of semi-infinite photonic crystals and are located on the surface of a PC. Employing surfaces of photonic crystals as waveguides may open up new possibilities for design and operation of photonic structures for feeding and redistributing light in PCs.

Surface states reside at the interface between a photonic crystal and open space, decaying into both media and propagating along the boundary. In a square lattice photonic crystal the surface states appear in the bandgap when a boundary of a PC is modified in some way, by, e.g., truncating the surface rods, shrinking or increasing their size, or creating more complex surface geometry [3]. The surface modes in a semi-infinite photonic crystal represent truly Bloch states with the infinite lifetime and Q factor, and consequently do not couple to incoming/outgoing radiation. At the same time, it has been demonstrated that when the translational symmetry along the boundary of the semi-infinite crystal is broken, the surface mode turns into a resonant state with a finite lifetime, which can be utilized for lasing and sensing applications [11, 12]. It has also been recently shown that with the help of surface modes it is possible to achieve directional beaming from the waveguide opening on the modified surface of a photonic crystal [13]. Surface states there, coupled with outgoing waveguide radiation, suppress diffraction and focus outgoing beam. At the same time, so far there have been no reports on study of guiding properties of PC surfaces.

In order to study surface states in photonic crystals, we apply a novel computational method based on the recursive Green’s function technique [11]. The advantage of this method is that it allows us to calculate and use surface Bloch modes as scattering states of the system, which makes it possible to compute the transmission coefficients for surface modes and corresponding field distributions.

![Band structures for TM modes in ΓX direction of a square-lattice photonic crystals composed of rods diameter d = 0.4a and permittivity ε = 8.9 along with the projected surface modes. The diameter of the surface rods is (a) d = 0.2a and (b) d = 0.68a.](image)

FIG. 1: (color online) Band structures for TM modes in ΓX direction of a square-lattice photonic crystals composed of rods diameter $D = 0.4a$ and permittivity $\varepsilon = 8.9$ along with the projected surface modes. The diameter of the surface rods is (a) $d = 0.2a$ and (b) $d = 0.68a$. The fat line denotes the light line. Lower panel shows the normalized intensity of $E_x$ component in different points of surface-mode dispersion curves.

Surface band structure. We consider a semi-infinite square-lattice photonic crystal composed of cylinders with $\varepsilon = 8.9$ and diameter $D = 0.4a$ ($a$ is a lattice constant) in air background. We study two different surface geometries supporting the surface states where the outmost rods has (a) reduced diameter $d = 0.2a$ and (b) enlarged $d = 0.68a$. This photonic crystal has a fundamental bandgap for TM-polarization in the range $0.33 < \omega a/2\pi c < 0.44$ and supports one surface mode for case (a), and two modes for case (b) as shown in Fig. 1. The surface modes for these two structures shows different patterns of field localization. For structure (a) the
field intensity has one maximum within each rod and extends into the air, quickly decaying into the crystal. For low energies a significant part of the field intensity extends into a wide $\sim 5-10a$ air layer near the surface of the PC. This can be apparently attributed to the proximity between the dispersion curve of the surface state and the light line, where the group velocity of the surface state, $v = \partial E/\partial k$, is close to $c$, see Fig. 1(a) and Fig. 2(a). As the energy increases, the dispersion curve moves away from the light line, and the field becomes mainly concentrated on the surface rods. For the case of the structure (b) with enlarged surface rods, the field is mostly located within each cylinder and has a node oriented either horizontally (mode I) or vertically (mode II), see Fig. 1(b). In contrast with case (a) the intensity of both surface modes is mainly localized within the surface rods and its extent to the air is small for the whole energy range.

Let us concentrate now on the surface mode dispersion and the intensity distribution in structures with reduced and enlarged surface cylinders. To this end, we construct two test photonic crystals entirely consisting of corresponding surface rods (i.e. with diameters $a = 0.2a$ and $a = 0.68a$). Their band structures along with the projected surface modes of the semi-infinite photonic crystal of Fig. 1 are represented in Fig. 2. The dispersion curve of the surface state for the structure (a) begins at the light line and remains nearly linear up to $\omega a/2\pi c \lesssim 0.40$, where its slope slowly decreases and finally reaches zero. Figure 2(a), demonstrate that the shape of the surface state closely follows the valence band of the test crystal in the $\Gamma X$ direction. The same situation holds also for structure (b), where both surface bands mimic the bulk levels in the conduction band of the corresponding test PC (given in Fig. 2(b)). Field distributions for corresponding bands are given as the insets to Fig. 2 and outline the relations between surface-state bands and corresponding bands of test PCs. It is worth mentioning that both surface bands for structure (b) have lower velocity in comparison to structure (a). Fast surface states are known as the most suitable for waveguiding applications, whereas slow modes can rather attract interest in structures for "slowing light" or in surface-state cavities.

FIG. 2: (color online) Fragments of the band structures for TM modes in $\Gamma X$ direction of infinite square-lattice test photonic crystals composed of rods with $\varepsilon = 8.9$ and diameter (a) $d = 0.2a$, (b) $d = 0.68a$ along with the projected surface modes of the semi-infinite photonic crystal of Fig. 1. Field distributions ($E_z$-components) for corresponding bands are given as the insets.

![Image](image_url)

**FIG. 3:** (color online) (a) Velocity of different surface modes from Fig. 1. (b) Transmission coefficient for surface modes propagating in a non-ideal surface-mode waveguide. Inset shows the structure under study, where the shaded regions denote ideal semi-infinite waveguides, and the central region of the width of $5a$ represents an imperfect photonic crystal where scattering of the Bloch surface states takes place.

**Effect of inhomogeneities.** Let us focus on the effect of inhomogeneities of the PC (imperfections in a shape of the rods, their displacement, or variation of the refraction index throughout the crystal, etc.) on the waveguiding properties of surface states. It has been demonstrated previously that such imperfections strongly affect the performance of lasing microcavities. We will show below that such the imperfections can cause a profound impact on the waveguiding efficiency of the surface modes.

In order to study the effects of imperfections, we divide the system under study into three regions as shown in the inset to Fig. 3. Two of them are left and right semi-infinite periodic structures (perfect waveguides for surface modes), and the block of the PC in between is an imperfect region. Utilization of the Green’s function technique allows us to use surface Bloch modes as scattering states that propagate in perfect waveguides from the infinity into the imperfect region where they undergo scattering. Obviously, in the case when the scattering region is absent (perfect waveguides are attached to each other), the Bloch states propagate freely without any scattering.

Because the model is numerical, the discretization of the circular rods of PCs can not be perfect and thus can be treated as inhomogeneities or roughness of the
structure. Note that the periodic waveguides are also discretized, but their discretization is deliberately chosen differently from that for the central region. The central scattering region represents a photonic crystal of a width of 5 unit cells, each of them being discretized into 25 meshes (≈ λ/50) in both x and y directions. Fig. 4 shows the velocities of surface states in both structures and corresponding transmission coefficients. (We note that when the discretization of each cell in the central region is chosen the same as for unit cells in the left and right waveguides, the transmission coefficients through the structure is unity).

The transmission coefficients for each surface mode drop quite rapidly in the energy regions corresponding to the low velocity of the surface state. This is because the backscattering probability is greatly enhanced for the low-speed states. Slow states for structure with enlarged surface rods are the most strongly affected. Even for 5 imperfect unit cells the transmission coefficients for both modes approaches 1 only in very narrow energy range, which makes these states hardly appropriate for waveguiding purposes. At the same time the transmission coefficient for the fast surface state in the structure (a) with the reduced boundary rods remains 1 in a wide energy region up to ωa/2πc ≈ 0.40, which makes it better candidate for waveguiding applications.

Applications of surface-state waveguides: Light coupler. Due to a unique location on the surface of the PC, surface-state waveguides can be exploited in a variety of novel applications. In this letter we focus on two of them, introducing novel light lead-in structure and sketching the possibility to use a surface-state waveguide as a directional emitter.

Feeding light into waveguides in photonic crystals composed of dielectric rods in air background is a complicated challenge, as normally it requires extremely accurate positioning of a dielectric waveguide and precise mode matching [17, 18]. Even in this case diffraction at the waveguide termination usually hampers coupling, and the efficiency of such lead-in systems hardly exceeds 60%. Other coupling techniques, like utilization of adiabatic dielectric tapers [19] can improve the device performance but exhibits high sensitivity to parameters of the tapers.

In this letter we propose a novel coupler based on waveguiding properties of surface states. Figure 4 illustrates such a lead-in structure composed of a surface-state waveguide to the left and a conventional tapered PC waveguide to the right. The diameter of the surface rods in the surface-state waveguide gradually decreases to zero in the region of the conventional PC waveguide as shown in Fig. 4. In this device an incoming state in the surface-mode waveguide region enters a tapered region where it is adiabatically transformed into conventional waveguiding state.

The maximum achieved transmission reaches T ≈ 0.8, see inset to Fig. 4. We should also mention that careful optimization of the surface geometry may further improve the performance of surface-state waveguide couplers, but such the work is out of the scope of the present Letter. We also note that our 2D calculations do not account for the radiative decay in the direction perpendicular to the plane of the photonic crystal.

Applications of surface-state waveguides: Directional emitter. The width of a conventional waveguide in PC is of the order of wavelength of light λ. Because of this, the beam launched from a semi-infinite photonic crystal into open space is diffracted at the waveguide opening in a strong angular spread ∼ 2π. It has been recently shown that it is possible to achieve directional emission out of a PC waveguides with corrugated terminations supporting leaky or evanescent surface states [13, 14]. We demonstrate below that directional emission with the angular spread much less than in conventional waveguides can also be achieved for the case of surface-state waveguides coupled to air. Figure 5 shows $E_z$ field intensity and directional diagram for the surface state propagating in semi-infinite waveguide corresponding to the structure (a) with the surface rods of a reduced diameter. The most of the beam intensity is localized within a range $\Delta \Theta \sim 20^\circ$. It should be also noted that the coupling of the surface state to air is rather high. Inset to Fig. 5 shows the transmission coefficient for the surface state in the semi-infinite surface waveguide propagating into open space. $T$ is close to unity in the energy region corresponding to high velocity of the surface state and drops rapidly for energies $\omega a/2\pi c \gtrsim 0.40$ where the velocity of the surface state decreases.

For the case of PC waveguides with corrugated terminations the directional emission is achieved as the result of the coupling between the incident beam in the
waveguide with the surface modes on the PC termination that causes the destructive interference for all directions except a narrow beaming cone \[13\,14\]. (Note that a mechanism of the directional beaming in PC waveguides is conceptually similar to that one in a subwavelength aperture in corrugated metallic films, where the incident beam is coupled to the surface plasmons residing at the corrugated boundary \[20\,21\]).

The origin of a rather narrow beaming cone for the case of surface-state waveguides is related to the fact that the surface state is localized in a wide spatial region near the surface \(a \sim 10a\) (as opposed to conventional waveguides whose width is typically \(\sim a\)), see Fig. 11. The angular spread in this case due to the diffraction, \(\sin \theta \sim \frac{\lambda}{10a}\), is consistent with the calculated far-field radial distribution of the Poynting vector. As the frequency of the incoming light increases, the surface mode becomes more localized, and the spread of the outgoing radiation increases. The effect of directional beaming in surface-mode waveguides might find its practical application for integration of PC-based devices with conventional fiber-optic devices.

**Conclusions** We put forward a novel concept for waveguiding structures based on surface modes in the bandgap photonic crystal structures. We analyze surface mode band structure, field localization and effect of imperfections on the waveguiding properties of the surface modes. To illustrate applications of the surface-state waveguides we suggest a new principle for feeding light into a photonic crystal waveguide and demonstrate that a semi-infinite surface-state waveguide can be used as a directional emitter.

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