Coupling into the slow light mode in slab-type photonic crystal waveguides

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Coupling external light signals into a photonic crystal (PhC) waveguide becomes increasingly inefficient as the group velocity of the waveguiding mode slow s down. We have systematically studied the efficiency of coupling in the slow light regime for samples with different truncations of the photonic lattice at the coupling interface between a strip waveguide and a PhC waveguide. An inverse power law dependence is found to best fit the experimental scaling of the coupling loss on the group index. Coupling efficiency is significantly improved up to group indices of 100 for a truncation of the lattice that favors the appearance of photonic surface states at the coupling interface in resonance with the slow light mode.

Planar two-dimensional (2D) slab-type photonic crystals (PhC) have attracted much attention recently as a possible platform for densely integrated photonic circuits. Engineering of the photonic dispersion utilized in planar devices might provide unique functionalities for integrated photonics unattainable with conventional approaches. For example slowing down the propagation velocity of light in PhC waveguides has been proposed for compact delay lines and all-optical storage devices. However, increase of the group index in the slow light regime prevents efficient coupling into the PhC waveguide due to increasingly large impedance mismatch. Several recent theoretical studies indicate that the exact termination of the photonic lattice at the coupling interface is important for improving impedance matching. It has also been suggested that surface states localized at the PhC interface can play a significant role in the coupling process.

In this Letter we study experimentally the dependence of the coupling efficiency on the group index for different terminations of the photonic lattice. Further we explore the possibility to improve mode matching and obtain efficient coupling by tuning the photonic surface states at the PhC interface in resonance with the slow light mode.

To experimentally study the coupling efficiency, PhC structures were fabricated on a silicon-on insulator 200nm wafer with 1μm BOX layer on a standard CMOS fabrication line as described elsewhere. PhCs with a triangular lattice of period a=437nm were defined by etching holes with radius R=109nm through a silicon layer with thickness d=225nm. PhC waveguides were formed by omitting one row of holes (W1 waveguide) in the lattice along the Γ-K direction. In order to probe the influence of surface termination, a set of samples was fabricated in which the truncation of the PhC waveguides at the strip/PhC interface was varied by changing the termination parameter from τ=0 to τ=1 as shown in the inset of Fig.1. The length of the PhC W1 waveguides L was kept approximately constant with 22 full unit cells (10μm). Light from a broadband source (four coupled LEDs with 50nm linewidth each) was coupled in and out of the photonic chip through polymer-based inverted fiber couplers using tapered and micro-lensed PM fibers. High resolution spectra were also measured with a tunable diode laser having a 100MHz linewidth. Access strip waveguides with 460x220nm cross-section are butt-coupled to the PhC W1 waveguides through a lateral taper with the final width of 757nm corresponding to \( \sqrt{3}a \). Transmission spectra from the PhC waveguide circuits were normalized on the transmission spectrum of a strip waveguide circuit without a PhC. Owing to small side-wall surface roughness with standard deviation 1.5nm as measured with an AFM, the propagation loss in analogous strip waveguide and PhC waveguide has been measured recently to be as low as 8±2db/cm and 5±0.2db/cm at 1650nm, correspondingly.

The inset of Fig.1 presents a set of transmission spectra...
recorded with optical spectrum analyzer for TE polarized light for wavelengths ranging from 1300 to 1700nm. As is seen, the spectra for samples with terminations \( \tau = 0, \tau = 0.5, \) and \( \tau = 0.75 \) are almost identical for most of the wavelengths. Spectra exhibit a sharp cutoff at 1670nm corresponding to the onset of the W1 waveguiding mode. It is seen that at wavelengths around 1600nm coupling at strip/PhC interface is almost perfect \( 0.3 \pm 0.1 \) dB for all the terminations. This excellent coupling is not surprising since the width of the access strip waveguide is chosen to match closely both the geometrical spread of the mode in the PhC waveguide and its group index far from the slow light regime.

At wavelengths longer than approximately 1600nm and closer to the waveguide onset cutoff at 1670nm a notable difference in the spectra is observed. This region corresponds to where the wavevectors \( k \) approach the Brillouin zone edge, and is characterized by an increasingly slow group velocity. Figure 1 shows the same set of transmission spectra for this wavelength range measured with an LED source with a spectral resolution of 60pm. Strong Fabry-Perot oscillations, especially noticeable for the spectrum of the sample with \( \tau = 0.5 \), are observed indicating large reflections at the coupling interface. The distance between minima and maxima \( \Delta \) of the oscillations is decreasing from 10nm to below 1nm towards the mode onset cut-off indicative of an increasingly small group velocity. The spectral positions of the maxima and minima of the oscillations can be used to extract the spectral dependence of the group index as \( n_g = \lambda^2 / (4 \Delta \lambda) \). Group indices approaching 100 are typical for the last visible maxima around 1667nm. It is also seen that the amplitudes of the maxima \( I_{\text{max}} \) and minima \( I_{\text{min}} \) are gradually decreasing toward the cut-off, while \( V \), the fringe visibility \( V = (I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}}) \), is actually increasing toward the cutoff approaching 0.8 for the last fringes around 1676nm. The latter indicates that the fringe amplitude is not seriously affected by the low coherence of the LED source (50nm line width). This is confirmed by comparison with spectra measured with high-coherence tunable laser shown in the inset of Fig.2.

Comparison of fringe maxima in the spectra for different terminations in Fig.1 implies that contribution of propagation losses is negligible. Indeed the fringe maxima differ by almost 10dB in the spectra (for example for \( \tau = 0 \) and \( \tau = 0.5 \)), while the length of the PhC waveguide \( L \) is identical (note the identical spectral positions of maxima and minima). If transmission losses in the slow light regime were the dominant source of loss we would expect fringe amplitudes measured at the same wavelength to be identical for different terminations, the opposite of what we observe experimentally.

The evident difference in the amplitude of the maxima for samples with different termination indicates that the main source of damping is increasingly inefficient coupling at the PhC/strip interface. If we assume that the propagation losses inside the PhC are negligible the amplitude of the maxima corresponds to the combined coupling losses at the input and output PhC/strip interfaces. Figure 2a presents a log-log plot of the coupling losses (amplitude of fringe maxima) as a function of the group index for PhC waveguides with different terminations. The reflectivity \( R \) of the PhC/strip interface can also be extracted from the fringe visibility \( V = 2R / (1 + R^2) \) assuming that the reflectivities of the input and output interfaces are equal. The dependence of the interface reflectivity \( R \) on the group index is shown in Fig.2b. Three different samples were measured for each termination.

Although visible even in Fig.1 the differences between different terminations become evident analyzing Fig.2a. Here the experimental dependence of coupling efficiency on the termination is best fitted with inverse power law dependence, which gives the exponent -0.99 and -1.84 for \( \tau = 0 \) and 0.5, respectively. The best coupling though is provided by the termination \( \tau = 0.75 \) where the fitting gives exponent as -0.72. Surprisingly there is no noticeable dependence of interface reflectivity on termination as seen in Fig.2b. To the best of our knowledge these are the first experimental measurements of both coupling and reflectivity of the PhC interface in the slow light regime.

Several recent publications examined theoretically the coupling efficiency of the strip/PhC interface for different terminations of the lattice. Although the slow light regime was intentionally omitted from consideration, for frequencies far from the mode cut-off it has been shown that terminations around \( \tau = 0 \) are preferred over \( \tau = 0.5 \). It has been argued that this is a result of bet-
seen from Fig.3 that the surface states appear in the photonic gap with dispersion (Fig.3b) and spectral position (Fig.3c) depending strongly on the termination parameter. The truncations $\tau=0$, 0.5 and $\tau=1$ correspond to surface states tuned to frequencies much higher than the PhC mode. Surface states do not contribute to propagation at the strip/PhC interface and these terminations are equivalent in this respect. Terminations around $\tau=0.25$ and $\tau=0.75$, however are characterized by surface states tuned almost in resonance with the PhC waveguide slow light mode. Moreover the surface state dispersion is almost flat at these frequencies reflecting the strong localization of the surface mode within only a few periods from the interface. Correspondingly not only is the impedance at the PhC termination strongly modified by the presence of surface states, but the group indices of the PhC slow light mode and surface states are also nearly matched. Based on these observations we can argue that experimentally measured performance indicate that surface states do play a significant role in coupling.

In conclusion we have experimentally measured coupling efficiency and reflectivity at the strip/PhC interface in the slow light regime. A strong inverse power law dependence of the coupling efficiency on group index was found for different terminations of the PhC lattice at the interface. Experimental results and theoretical calculations suggest that terminations with photonic surface states tuned in resonance with the PhC slow light mode provide the best coupling efficiency. This finding can shed light on many other coupling phenomena in PhC like, for example, recently discovered beaming and focusing of light exiting the 2D PhC waveguide structure.

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