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Efficient light coupling into a photonic crystal waveguide with flatband slow mode

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Abstract

We design an efficient coupler to transmit light from a strip waveguide into the flatband slow mode of a photonic crystal waveguide with ring-shaped holes. The coupler is a section of a photonic crystal waveguide with a higher group velocity, obtained by different ring dimensions. We demonstrate coupling efficiency in excess of 95% over the 8 nm wavelength range where the photonic crystal waveguide exhibits a quasi-constant group velocity $v_g \approx c/37$ and observe a more than 12-fold intensity enhancement in the slow-light waveguide. An analysis based on the small Fabry–Pérot resonances in the simulated transmission spectra is used for studying the effect of the coupler length and for evaluating the coupling efficiency in different parts of the coupler. The mode conversion efficiency within the coupler is more than 99.7% over the wavelength range of interest. The parasitic reflectance in the coupler, which depends on the propagation constant mismatch between the slow mode and the coupler mode, is lower than 0.6%.

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1. Introduction

Photonic crystal waveguides (PhCWs) exhibit slow optical modes with group velocities at least one order of magnitude smaller than in conventional waveguides [1–5]. Enhanced nonlinearity effects have been demonstrated for slow modes, which may allow scaling down the size of active integrated optics devices [6,7]. Slow modes can be used in telecommunication systems provided that they have sufficiently low group velocity dispersion (GVD), and PhCWs with such flatband slow modes have recently been designed [8–10]. We have designed a waveguide based on a photonic crystal with ring-shaped holes (RPhCW) with low GVD and group velocity $v_g \approx c/37$ over a wavelength range of several nanometers [11]. The feasibility of the RPhCW was shown in [12], where we observed slow-light propagation in an RPhCW fabricated on a silicon-on-insulator substrate.

Efficient coupling between waveguides with different group velocities is not trivial [13–16]. Transmission from strip waveguides (SWs) to slow modes in PhCWs

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can be improved by optimizing the termination of the PhCW [13], tapering the PhCW [15] and by using high group velocity PhCWs at both ends of the slow-light PhCW [16]. In these examples, efficient coupling into slow modes in PhCWs was achieved with couplers significantly shorter than required for adiabatic mode conversion. De Sterke et al. [17] and Velha et al. [18] showed that perfect coupling could be achieved by utilizing the interference between the forward and backward propagating modes in the coupler. Hugonin et al. [19] noticed the appearance of a transient zone a few lattice periods long at the interface between PhCW sections of different group velocities, where light is smoothly slowed down as it penetrates the slow-light waveguide, and they demonstrated efficient mode conversion in such a structure. This approach makes it possible to optimize the different interfaces of the slow-light device independently.

In this paper we design an efficient coupler into the slow, dispersion engineered mode with a nearly constant v_g in the RPhCW presented in [11]. We present a simple way of studying coupling efficiencies in different parts of the coupler, based on the small Fabry–Pérot (F–P) resonances in the transmission spectrum.

2. Coupler design

2.1. Group velocity in RPhC waveguides

Fig. 1 shows a schematic of an RPhCW defined by one missing row of holes in an otherwise perfect RPhC. The RPhC is a triangular lattice of rings with a lattice constant a. The ring is defined by two parameters, ring outer and inner radii R_{out} and R_{in}, respectively. The RPhCW is coupled to SWs with width w at the interface. The parameter d defines the position at which the RPhCW is terminated.

Band structures of the RPhCWs are calculated using the plane wave expansion (PWE) method described in [20]. The PWE simulations yield dispersion relations $u(\beta)$, where u is the normalized frequency $u = a/\lambda$ and β is the propagation constant. The group velocity v_g is defined as

$$v_g = \frac{d\omega}{d\beta} = \frac{2\pi c}{a}\frac{du}{d\beta}. \quad (1)$$

Therefore, v_g is directly proportional to the slope of the dispersion curve in Fig. 2, where we plot the dispersion relation of the even TE polarized mode (electric field in the propagation plane) in RPhCWs with different values of R_{out}. The ring width is kept constant at $R_{out} - R_{in} = 0.15a$. The simulations were carried out in 2D for the TE polarization. An effective index of the dielectric material equal to $n_{eff} = 3.178$ was used, corresponding to the effective refractive index of a 400 nm thick silicon ($n_{Si} = 3.48$) slab on silica ($n_{SiO_2} = 1.46$) at the wavelength of 1550 nm.

We have demonstrated in our previous work that an RPhCW with $R_{out} = 0.385a$ and $R_{in} = 0.235a$ exhibits a flatband mode with a quasi-constant and relatively low group velocity $v_g \approx c/37$ over a wavelength range of 8 nm [11]. The frequency range corresponding to the nearly constant v_g is between the normalized frequencies $u = 0.250$ and 0.2512 and it is highlighted in Fig. 2. The v_g values in this paper are given for this frequency range, unless the frequency or propagation constant range is explicitly specified. With a lattice constant $a = 392$ nm, which we will use later in this paper, the range of nearly constant v_g lies between wavelengths 1560 and 1568 nm.

For all waveguides in Fig. 2, the even mode is in the index-guided regime with $v_g \approx c/3.8$ when $\beta < 0.32(2\pi/a)$. When approaching the Brillouin zone edge at $\beta = 0.5(2\pi/a)$, the mode becomes diffraction-guided: v_g decreases and eventually vanishes when $\beta = 0.5(2\pi/a)$. If R_{out} is decreased, the air-fill factor of

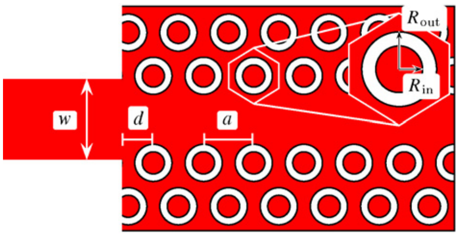

Fig. 1. Schematic of a W1 RPhC with an input strip waveguide.

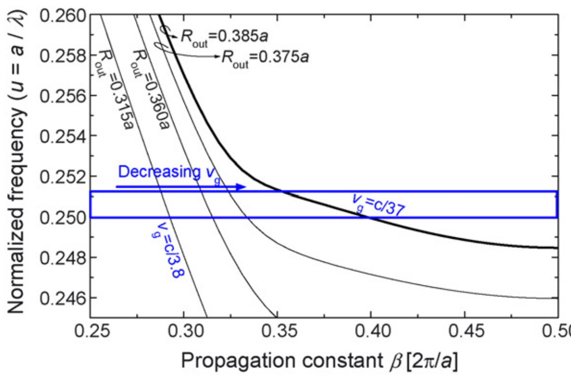

Fig. 2. Dispersion relation of the even mode in RPhCWs with different outer radius R_{out}. The ring width $R_{out} - R_{in} = 0.15a$ for all waveguides. In the normalized frequency range within the frame, the average group velocity decreases from $v_g = c/3.8$ when $R_{out} = 0.315a$ to $v_g = c/37$ when $R_{out} = 0.385a$.