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Direct slow-light excitation in photonic crystal waveguides forming ultra-compact splitters

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Abstract: Based on a series of 1x2 beam splitters, novel direct excitation of slow-light from input- to output-region in photonic crystal waveguides is investigated theoretically and experimentally. The study shows that the slow-light excitation provides over 50 nm bandwidth for TE-polarized light splitting between two output ports, and co-exists together with self-imaging leading to ~20 nm extra bandwidth. The intensity of the direct excitation is qualitatively explained by the overlap integral of the magnetic fields between the ground input- and excited output-modes. The direct excitation of slow light is practically lossless compared with transmission in a W1 photonic crystal waveguides, which broadens the application-field for slow-light and further minimizes the size of a 1x2 splitter.

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References and links
1. Introduction

Silicon has shown promising advantages in Photonic Integrated Circuits (PICs) because of its compatibility with CMOS electronics, which provides a mature fabrication platform for silicon optics components. Photonic band-gaps (PBGs), namely Photonic Crystals (PhCs), forbid some wavelength bands to propagate via the interaction between the light and nano-structured material. The effective range of PBG is controllable and modulatable. Line-defect photonic crystal waveguides (PhCWs) confine light within the PBG to the line-defect irrespectively of propagation direction. The most common design is obtained by removing exactly one row of air-holes, known as W1 PhCW. Slow light in PhCW with high dispersion offers a promising approach for on-chip integration of ultra-compact components [1].

Beam splitters are indispensable in PICs, and a 1x2 splitter is the most fundamental one. These components have been designed and fabricated using PhC [2–10], including direct splitting, such as Y-junctions [2–5] and T-junctions [6], and directional couplers [7,8]. Multi-mode interference (MMI) based on the self-imaging principle, is also widely adopted [7–10]. MMI in PhCWs with every-second-line-defect regions further shortens the coupling length [9–11]. Recently, the first 1x3 PhCW splitter was fabricated and measured by the authors [12]. Here we present the novel direct excitation of slow-light in PhCWs, which provides a more broadband splitting operation than self-imaging. Direct excitation can take place along side MMI self-imaging; however, the minimum splitter can be purely composed of input- and output-regions thereby completely omitting the MMI effect. The splitters are analyzed in terms of MMI self-imaging before the effect of the direct excitation is described.

2. Self-imaging for directional coupling in multi-mode region

Self-imaging occurs from the supermodes that result from MMI. Excitation between modes only happens when two or more modes have the same symmetry and exist at the same frequency in a multi-mode region. On the basis of directional coupling [9], the superposition of the excited modes for two-fold imaging is expressed as:

$$\psi(x, z) = c_0\psi_{m_0}(x, z)e^{-j\beta_{m_0}z} + c_2\psi_{m_2}(x, z)e^{-j\beta_{m_2}z},$$  \hspace{1cm} (1)

where \(c_n\) is the field excitation coefficient, \(c_n\psi_{m_n}(x, z)e^{-j\beta_{m_n}z}\) is the localized Bloch wave function with propagation constant of \(\beta_{m_n}\) and the subscript \(m\) = 0 or 2 denotes the order of the mode. Self-imaging in PhCW occurs at specific coupling lengths, \(L_n\), where \(n\) is an integer representing the number of self-images that have occurred from the beginning of MMI region. The shortest coupling length, \(L_0\), to provide a two-fold image is derived from a relationship between different propagation constants and, for the two lowest modes, 0th and 2nd, can be written as:

$$L_0 = \frac{\pi}{|\beta_0 - \beta_2|},$$  \hspace{1cm} (2)

where \(\beta_0\) is for the 0th mode and \(\beta_2\) for 2nd mode.

One crucial feature of a PhCW is its nonlinear dispersion, different from conventional index-guiding silicon waveguide for which the dispersion relation of the modes is much closer to a straight line \(\omega = ck\). The dispersion relations \(\omega(k)\) for a given PhCW system is related to the effective speed of light \(c\) in the waveguide with frequency \(\omega\) and wave vector \(k\) [13]. The group velocity \(v_g\) of light with frequency \(\omega\) in the optical waveguide is given as:

$$v_g = \frac{d\sigma}{dk} = \frac{c_0}{n_g},$$  \hspace{1cm} (3)
where $k$ is the wave vector along the waveguide and $n_g$ the group index.

Fig. 1. Dispersion diagram for the even guided TE polarization of the PhCWs calculated using 3D PWE method, where the right axis shows the corresponding wavelength, $\lambda$, in free space for $\Lambda = 380$ nm. a) the single W1 PhCW, b) the triple multimode region, and c) the dual waveguide output. The super-cells are shown in the insets. The upper cyan shaded band indicates the region where the MMI self-imaging can occur in MMI region and the gray part represents the region where the novel excitation may happen.

The group velocity of the PhCW can be interpreted from dispersion diagrams representing normalized wave vector and frequency. Figure 1 presents the in-plane normalized dispersion diagrams along the defect direction ($z$) for the proposed single- and multi-mode PhCWs with $D/\Lambda = 0.558$, where $D$ is the diameter of the holes and $\Lambda$ is the lattice pitch, calculated by the 3D plane wave expansion (PWE) method with a grid spacing of $\Lambda/16$. The 1x2 splitters are generally composed of three kinds of PhCW regions (refer to Fig. 2(a)). The corresponding super-cells are depicted in the inserts of Fig. 1.

Figure 1(a) and 1(c) represent the input- and output-regions. If the lattice pitch is $\Lambda = 380$ nm and the silicon layer is 340 nm thick, the theoretical cutoff of a W1 PhCW is around 1596 nm ($\Lambda/\lambda = 0.2381$). It is shown in Fig. 1(b) that a multimode region exists for the 0th and 2nd even modes, and therefore multimode interference is possible over the frequency range where both modes exists. This means that the potential excitation for self-imaging between 0th and 2nd modes can take place in the range between 1520 and 1560 nm (upper cyan band in Fig. 1(b)). The beat length, $L_0$ in the MMI region at 1560 nm corresponds to over 20$\Lambda$. In order to shorten the beat length, the difference between $\beta_0$ and $\beta_2$ needs to increase. The excitation must move to a shorter wavelength in order to increase the difference between $\beta_0$ and $\beta_2$. The shortest beat length integer is 6$\Lambda$ at the lowest wavelength, which is approximately 1522 nm for the corresponding beat length.

Fig. 2. (a)-(c) SEM micrographs of splitters with $L_0 = 0, 3$ and 7$\Lambda$.

Some of the designed splitters, with coupling lengths of $L_0 = 5-9$ and 14$\Lambda$, have been fabricated in the 340-nm silicon layer of a SOI wafer on 2 $\mu$m buried silica. The details of the fabrication and measurements can be found in ref [12]. The air holes of the fabricated PhCW splitter have a diameter of ~212 nm. The same output layout of the splitters, and similar decoupling cosine shaped ridge waveguides were adopted as in ref [12]. The width of the ridge waveguides connected to/from the splitters is around 0.54 $\mu$m. A pure ridge waveguide
was also fabricated as the reference waveguide, together with a W1 PhCW with the same parameters of the PhC with \( \sim 10 \mu m \) length.

The measured cut-off wavelength of the W1 PhCWs is about 1590 nm with a drop of 30 dB. The transmittance of the pure ridge waveguide was used as a reference, which means its loss is 0 dB in the range from 1500 to 1620 nm. The normalized transmittance of the other PhCWs was used in the following discussion. The transmission of the W1 PhCW is shown in all the graphs for comparison between the splitters. The 1x2 splitter with a coupling length of 7\( \Lambda \) (Fig. 2(a)) was chosen to display the self-imaging transmission band, because it had slightly better performance characteristics, wider and higher transmission band around 1530 nm (shown in cyan pattern in the top of Fig. 3(b)) than the 6\( \Lambda \) splitter. The bandwidth of the two-fold imaging in the 7\( \Lambda \) splitter is around 20 nm and 11 nm for the three-fold MMI’s [12], which implies the four-fold and higher imaging will lead to a much narrower band. The peak of self-imaging transmittance red-shifts with an increase in coupling length \( L_0 \), up to \( \sim 1542 \) nm for the 14\( \Lambda \) splitter in complete agreement with the expectations.

![Fig. 3. (a) Simulated normalized TE-polarized transmission by 3D FDTD for the splitters (b) measured normalized TE-polarized transmission for the splitters. Self-imaging excitation bands are shown highlighted with cyan pattern.](image)

3. Direct slow-light excitation from input- to output-region

It is very interesting to note that the spectrum of the 7\( \Lambda \) splitter presents a second peak at lower frequency within the range until the cut-off of the corresponding W1 PhCW. The input power is split effectively in a range of over 50 nm and exhibits very similar total transmission intensity as a W1 PhCW. This novel broad band splitting is independent of the length of the MMI region and exists in all splitters with coupling lengths extending from 5\( \Lambda \) up to 14\( \Lambda \). This unexpectedly broadband transmission lies outside the 2nd mode’s frequency and therefore is not an artifact of self-imaging.

To further investigate the splitting, 3D FDTD modeling with a grid spacing of \( \Lambda/24 \) was executed to simulate the excitation in the splitters. The transmission of the splitters is again normalized to a ridge waveguide. The simulated spectrum of the splitter with \( L_0 = 7\Lambda \) is shown at the top of Fig. 3(a). It is clear to see that both the self-imaging and novel excitation bands exist and there is good agreement between the simulated and measured results, although the simulated spectra contain a red-shift of around 20 nm. The 5\( \Lambda \) splitter also presents the novel transmission band but no self-imaging peak in agreement with observations.

With apparent splitting existing in splitters shorter than the minimum coupling length for self-imaging, another two splitters with \( L = 3 \) and 0\( \Lambda \) (Fig. 2(b) and 2(c)) were simulated and fabricated to examine the transmission features. The reduced coupling-length ensures that
directional coupling is definitely impossible from self-imaging. The 04 splitter (Fig. 2(c)) is only composed of two parts, the single-mode input-region and the multi-mode output-region. The band of the novel excitation still exists and retains high transmission in the simulation results. Hence, its existence cannot be due to self-imaging, since self-imaging is length-dependent and requires a minimum length to function. The splitters were fabricated, and the measurements corroborate the high transmission and bandwidth (shown in Fig. 3(b)).

4. Discussion

The magnetic profile ($H_y$) of the guided-mode effectively illustrates mode coupling and splitting in MMI regions by presenting the dispersive difference at different $\omega$ and $k$ in the PhCW. The transverse profile of the magnetic field $H_y$ for the even modes supported by the super-cells in Fig. 1 were calculated by 2D PWE method. Figure 4 shows the modal field distributions for the even PBG modes in three different regions: index-guided, semi-slow and slow light, corresponding to the operating frequencies of ~0.255, 0.246 and 0.239($\Lambda/\lambda$), marked by colored squares in Fig. 1(a)-(c). Figure 4(a) show the 0th and 2nd even modes in the MMI region that are involved in MMI directional coupling. For slow light only the 0th mode is supported. Figure 4(b) show the supported even modes in the PhCW input- and output-regions that can facilitate direct excitation.

It is clear from the left part of Fig. 4(a) that for the index-guided mode in the MMI region, the 0th mode is well confined in the central defect between two rows of holes, quite similar to the W1 PhCW input-region (Fig. 4(b) left). The corresponding 2nd even mode distributes in the outer rows of the every-other-line-defect region, similar to the supported 0th even mode in the output-region (Fig. 4(b) left). The overlap between the two MMI even modes is very weak, so the length of directional coupling of self-imaging is quite long, as discussed in the ref [9]. For this situation, the interface differences between regions is definitely negligible. This is the case for directional coupling in ridge waveguides and is the reason why only the modes in the MMI region are employed to discuss the directional coupling.

At a frequency of $\Lambda/\lambda = 0.246$, the input-region mode (dark-yellow square in Fig. 1 and 4) is starting to penetrate into the first row of PhC holes and becomes a semi-slow mode. The distribution of the 0th MMI even mode locates somewhat in the outer rows of every-other-line defects. The overlap between the 0th and 2nd modes in the MMI region turns stronger and the coupling length is much shorter than in the index-guided regime, as the self-imaging excitation discussed in our samples. By utilizing the nonlinear dispersion in PhCW, the beat length of the MMI with every-second-line-defect region further decreases. It should be noted that the overlap of two even modes in the input- and output-regions is also enhanced with the overlap increase of two even modes in the MMI region.
Correspondingly the 0th mode at $\Lambda/\lambda = 0.239$ in the input-region enters a slow-light regime (yellow square in Fig. 1(a)), penetrating into the first and second row of holes in the photonic crystal with its field highly distributed in the first adjacent row. The slow-light mode is very sensitive to the presence of adjacent rows of holes, mainly to the first two rows of holes [2,13,14]. If the slow-light's frequency is closer to cutoff, the field profile with higher dispersion can penetrate through three rows of holes [15]. This highly dispersive character of slow light makes the existence of the 2nd even mode impossible in the proposed MMI regions.

The excitation from the input-region directly to the output-region, is still symmetry-allowed in principle, although this kind of direct excitation is normally very weak and for index-guided light it is also negligible in PhCWs (left part of Fig. 4(b)). However, slow light with its dispersive character contributes significantly to the overlap between the even modes in input- and output-regions and makes direct excitation more probable (right part of Fig. 4(b)). The intensity of the direct excitation varies with the overlap, so the transmission rises with increasing wavelength in the 0/1 splitter.

If the excitation is symmetrically permitted, the overlap integral of the magnetic field between the ground input- and excited output-mode ($H_g$ and $H_e$) can be used to qualitatively compare the transfer efficiency of the direct excitation. The overlap, $M$, is calculated according to:

$$M(\lambda) = \frac{\int H_g^*(\tau) H_e(\tau) d\tau}{\int H_g^*(\tau) H_g(\tau) d\tau \int H_e^*(\tau) H_e(\tau) d\tau}.$$

Within the region where the input mode exists and the overlap integral is high the wavevectors of the input and output waveguides match within 5%. Therefore the direct excitation is primarily governed by the overlap integral and small differences in wavevectors are relaxed during or soon after exciting the output-mode.

Figure 5 shows the calculated overlap based on two approximations: First to neglect the tiny difference of frequency between the corresponding eigenmodes of the supercells obtained from PWE method in the input- and output-regions. Second to assume that the transmittance of a W1 PhCW is a constant at all the wavelengths. The second assumption is generally acceptable until 1590 nm, seen from Fig. 3(a). The best overlap is found at 1570 nm, in good agreement with the results in Fig. 3.

Interestingly the direct excitation exists in all the splitters from $L_e = 0$ up to 14A. This implies that the MMI-region doesn’t prevent the direct excitation. The symmetric 0th even mode of slow light in MMI regions serves as a conjugated-bridge between the input- and output-regions. It also explains why the novel band co-exists with the self-imaging band.
When the light encounters the end of the defect in input-region temporally, its forward propagation is prevented by the PhC structure. It either reflects back or penetrates into the photonic crystal. Most light with low dispersion or in the index-guided regime will reflect back as it virtually has no penetration into the PhC structure, even without the in-between row of holes. This is the main loss mechanism for T- and Y-splitters in PhCW [6]. However, the slow- and semi-slow light with high dispersion is in another regime. The distribution of the mode field in the cladding of the PhC greatly contributes to the incident TE-polarized power crossing the in-between row of holes and subsequently distributes equally in the output waveguides. If the input- and output-regions are now separated by two PhC lattice periods, the maximum intensity of the output mode is still 20% compared with the 0/4 splitter based on the 3D FDTD simulation.

For conventional devices direct excitation is weak since it relies on a mechanism similar to barrier-penetration known from quantum-mechanical decay processes. However, it is greatly enhanced for the slow-light in good qualitative agreement with our 1x2 splitters.

4. Summary

Two transmission bands near 1550 nm in 1x2 splitters, based on slow-light direct excitation and multi-mode interference self-imaging effects in photonic crystal were discussed. The 1x2 splitter without splitting region based only on the direct excitation performs well across the entire transmission range, especially in the slow light regime near the cut-off wavelength around 1590 nm. The study shows that the delocalized propagation of slow-light plays a significant role in the 1x2 splitters and is a promising way to build splitters with a very small footprint, providing a larger transmission bandwidth than the self-imaging effect. This creates a new multi-functional application-field for ultra-small slow-light devices. Furthermore, the length of the 1x2 splitter is limited only by the minimum length of the input W1 PhCW.

In addition, the 1x2 splitter also works as a 2x1 combiner in the same bandwidth as long as the input modes have the same phase for both input arms and similar powers. The absolute loss in the splitters can be further reduced by removing the buried silica layer [16].

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