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Slow Light by Two-Dimensional Photonic Crystal Waveguides *

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A simple and effective way to measure the group velocity of photonic crystal waveguides (PCWGs) is developed by using a fiber Mach–Zehnder interferometer. A PCWG with perfect air-bridge structure is fabricated and slow light with group velocity slower than c/80 is demonstrated.

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Slow light is promising for various important applications[1−4] and has become an extensive research object. A two-dimensional (2D) photonic crystal waveguide (PCWG)[5,6] is an effective approach to obtain slow light because it can easily realize a large group index of several hundreds near the cut off wavelength of the foundational defect mode.[5]

It has been reported by several research groups that slow light is observed or measured in PCWGs. The group index was estimated from tens to several hundreds for different structures.[4,5,7] In 2001, Notomi *et al.*[5] observed slow light phenomena in a PCWG from Fabry–Perot (F-P) fringes caused by light reflection between the waveguide facets. In 2004, the same group measured the phase shift of a microwave signal modulated on the light transmitted through PCWGs and calculated the group index.[7] In 2005, Vlasov *et al.*[4] made an unbalanced Mach–Zehnder interferometer (MZI) by a PCWG, measured the interference fringe periods, and obtained a group index as large as 500.

In this Letter, we report a high quality air-bridge PCWG with low transmission loss. The group velocity was measured by a novel method using a fiber MZI and calculating the group index from fringe periods. Compared with other reported measurement methods,[4,5,7−9] the method proposed here can be constructed easily and avoids using expensive equipment or fabricating the interference structure on the chip. Slow light is successfully demonstrated with the air-bridge PCWG. The group velocity is estimated to be slower than $c/80$.

The air-bridge PCWG was fabricated on a SOI wafer, consisting of a 200-nm-thick silicon (Si) layer on a 3-μm buried silica (SiO_2) layer. The whole sample was comprised of a PCWG and joint strip waveguides from both ends of the PCWG. Using ZEP-520A as the resist mask, the pattern for both the PCWG and joint strip waveguides was generated by EB lithography. Then ICP dry etching was employed to transfer the pattern to the silicon film. After removing the resist mask, a 600-nm-thick SiO_2 cladding layer was deposited on the surface of the whole wafer. In order to fabricate the air-bridge structure and avoid undercut of SiO_2 below the strip waveguide, we used additional UV lithography to open the window for SiO_2 wet etching only in the PCWG region.

Figure 1 shows a SEM image of the fabricated PCWG with air-bridge structure. The PCWG has a period of 420 nm, hole radii of about 124 nm, and thickness of about 200 nm. The length of the PCWG is l_{pc} = 50.4 μm. There are 10 rows of holes in the x direction to form band gap confinement. It can be seen that the holes are well formed with very smooth sidewall, and the PCWG is successfully connected to the strip waveguide.

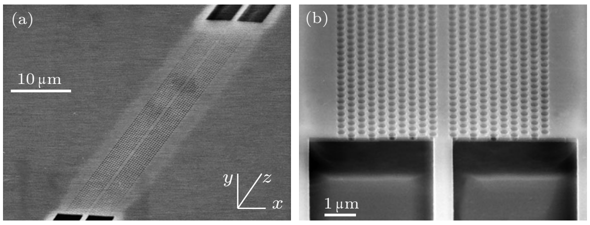

Fig. 1. High quality photonic crystal waveguide with air-bridge structure: (a) total view and the axis, (b) view at the joint facet of the strip WG and PCWG.

The transmission spectra of the PCWG from 1470 nm to 1500 nm were measured. The transmission spectra of the defect mode are shown in Fig. 4 with the gray line. It is expected that abnormal group velocity will be observed for the defect mode and slow light would exist near the mode edge.

The measurement system for group velocity is shown in Fig. 2. A wide band LED source was polarized and divided into two arms: one was the testing

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arm and the other was the reference arm. The PCWG was put on the testing arm with quite high coupling efficiency. A tunable attenuator and a tunable delay line were set in the reference arm to adjust the optical power and propagation distance, respectively, to form appropriate interference. The spectra were recorded by an optical spectrum analyzer (OSA). The F-P fringes of the measured sample can be smoothed by setting the resolution of the OSA to 0.2 nm, which is approximately equal to the F-P fringes of the waveguide sample.

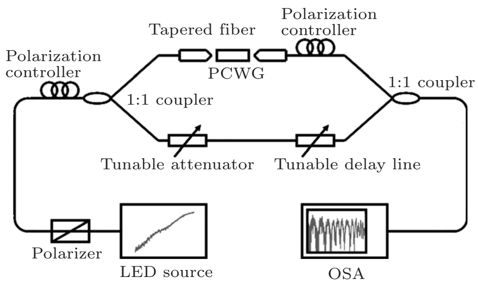

Fig. 2. Constitution of the fiber MZI group index measurement system.

An unbalanced MZI was formed by setting the propagation distance of the testing arm slightly longer than that of the reference arm. If the difference is l, the fringe pitch Λ satisfies

$$\beta(\lambda+\Lambda)l - \beta(\lambda)l = 2\pi, \quad (1)$$

where β is the average propagation factor with respect to wavelength λ. By Taylor expansion (ignore the second order and above), we have

$$\beta(\lambda+\Lambda) = \beta(\lambda) + \frac{d\beta}{d\lambda}\Lambda. \quad (2)$$

From Eqs. (1) and (2) we obtain

$$\frac{d\beta}{d\lambda}l = \frac{2\pi}{\Lambda}. \quad (3)$$

The group index can be expressed as

$$n_g = \frac{c}{v_g} = c\frac{d\beta}{d\omega} = c\frac{d\beta}{d\lambda}\cdot\frac{d\lambda}{d\omega} = \frac{\lambda^2}{2\pi}\frac{d\beta}{d\lambda} = \frac{\lambda^2}{\Lambda l}. \quad (4)$$

For the measurement system, we have

$$n_{gr}l_r + n_{gpc}l_{pc} = \frac{\lambda^2}{\Lambda}, \quad (5)$$

where $n_{gpc}l_{pc}$ is the effective propagation length of the PCWG region, and $n_{gr}l_r$ is that of the rest part of the testing arm, which almost does not change with wavelength.

For the wavelength region shorter than that of the defect mode (< 1470 nm), the group index of the PCWG can be considered to be about 10 according to the theoretical result.[4] While in the wavelength region of the defect mode, the group index of the PCWG can be expressed as

$$n_{gpc} = \Delta n_{gpc} + 10. \quad (6)$$

Therefore, using Eqs. (5) and (6), we can obtain n_{gpc} from different measured Λ.

Figure 3 shows the measured interference spectra. It can be seen that Λ decreases as the wavelength increases, which indicates that n_g changes with the wavelength due to the PCWG. The estimated group index of the PCWG is shown in Fig. 4. In order to eliminate the effect of the instability of the fiber MZI, we measured one sample five times, and plotted all the points in Fig. 4 to see the average result.

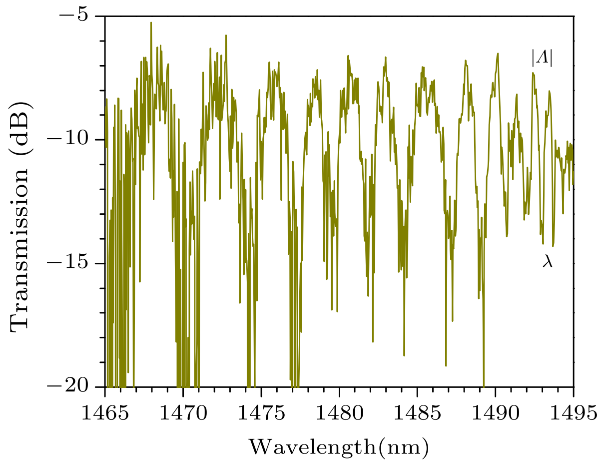

Fig. 3. Interference spectra measured by the OSA: the fluctuations of spectra are caused by the instability of the fiber MZI. Λ: fringe pitch at wavelength λ.

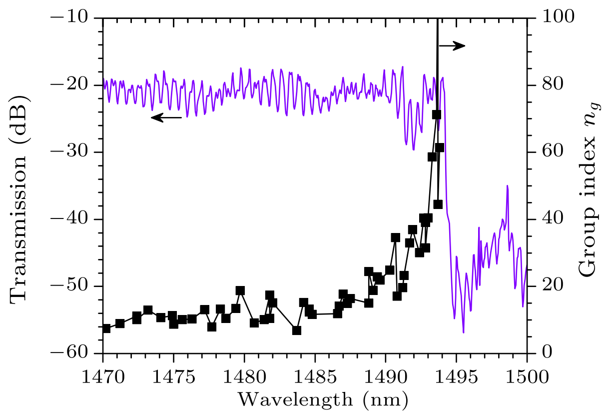

Fig. 4. Measured transmission spectra and group index of the PCWG. Gray line: transmission spectra. Black line with square symbol: group index.

Although there are some fluctuations, the black line in Fig. 4 shows the change of the group index depending on the wavelength. Corresponding to the transmission spectra of the defect mode, shown by the gray line in Fig. 4, the group index increases as the wavelength increases. We obtain a group index of larger than 80 at the edge of the defect mode. When the wavelength is longer than that of the defect mode, no interference exists because light cannot transmit through the PCWG. The group index fits the transmission spectra very well. Due to slower light suffering from more transmission loss, both the slow down factor and loss should be considered in the device design. Fluctuations in the measured group index could be reduced by shortening the fiber length to make the system more compact, and increasing the scan speed of the OSA.

In conclusion, we have fabricated a PCWG with perfect air-bridge structure and developed a simple and effective way to measure the group index of the PCWG by using a fiber MZI. For a PCWG with length 50.4 μm, slow light is realized successfully with a group velocity slower than $c/80$.

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