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Time-Domain Measurement of Optical True-Time Delay in Two-Dimensional Photonic Crystal Waveguides *

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We report on the realization of optical true-time delay (TTD) by a two-dimensional photonic crystal waveguide (PCWG). Design and fabrication of the PCWG are investigated. The spectral dependence of the group delay is measured by detecting the phase shifts of a 10 GHz modulating signal, and a maximum delay of 25 ± 2.5 *ps is obtained.*

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Optical true-time delay (TTD) techniques,[1,2] with the features of wide bandwidth, compact size, reduced system weight, and low electromagnetic interference, are expected to be useful in microwave photonics, e.g. phased-array beam shaping and optical signal processing systems. Many schemes have been proposed to provide optical TTD, including bulky optics,[3] slow light effect in fibers,[4] dispersive fibers,[5] photonic crystal fibers,[6] and fiber gratings,[7] etc.

A promising candidate for optical TTD devices is the two-dimensional (2D) photonic crystal waveguide (PCWG). In a PCWG-based TTD element, an optical carrier is modulated by the microwave signal and the group delay can be tuned by changing the carrier wavelength.[8,9] The size of the optical components can be greatly reduced because of the slow light (light with a low group velocity v_g)[10,11] effect in PCWGs. Moreover, such an approach avoids the severe pulse broadening and waveform distortion caused by group velocity dispersion (GVD)[12,13] because the spectrum of the modulated optical signal is relatively narrow and simple.

In this Letter, we report the measurement of optical TTD in an air-bridge PCWG by the time-domain modulation phase-shift method,[8,10] namely, detecting the phase shift of light sinusoidally modulated at gigahertz frequencies. A tunable group delay up to 25 ps is achieved and the output signal shows no evident waveform distortion. Such results demonstrate the potential of using PCWGs as building blocks in optical TTD systems.

The PCWG consists of a single line defect (W1) and triangular lattice air holes with period a = 440 nm, hole radius $r = 0.3a$ = 130 nm, and thickness h = 200 nm. These structural parameters were designed to set the slow light regime around λ = 1550 nm. The PCWG sample is as long as l = 475 µm (1080a) for obtaining large group delay. Figure 1 shows the calculated band structure for the transverse-electric (TE) polarization in Γ-K direction by 2D plane wave expansion (PWE) method[14] with an effective refractive index $n_{\rm eff} = 2.54$. It can be seen that the dispersion curve for the even defect mode becomes flatter near the band edge ($\omega a/2\pi c = 0.281$), which corresponds to the slow light regime. Below the band edge ($0.275 < \omega a/2\pi c < 0.281$) the band gap region lies.

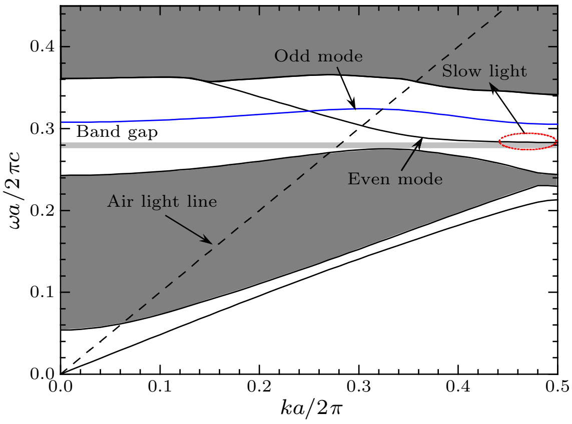

Fig. 1. Calculated TE band structure of W1 PCWG with $r/a = 0.3$. The dark area denotes the band gap and the red circle indicates the slow light regime.

The PCWG sample was fabricated on a silicon-on-insulator (SOI) wafer consisting of a 200-nm-thick silicon (Si) layer on a 3-µm buried silica (SiO_2) layer. The pattern of the photonic crystal and access strip waveguides was defined in ZEP-520A resist by electron beam (EB) lithography and then transferred into the silicon layer using inductively coupled plasma (ICP)

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dry etching with CF_4 and Ar mixture. A 600-nm-thick SiO_2 cladding layer was deposited on the surface of the whole wafer to protect the strip waveguides and to improve the coupling efficiency. Windows were opened in the photoresist above the PCWGs region and the underlying SiO_2 cladding was selectively removed using buffered hydrofluoric acid (BHF). Figure 2 shows a scanning electron microscope (SEM) image of the fabricated PCWG sample. The transmission spectrum of the defect mode in the PCWG from 1535 to 1560 nm is shown in Fig. 5 in black line. It is expected that low group velocity will be observed near the mode edge.

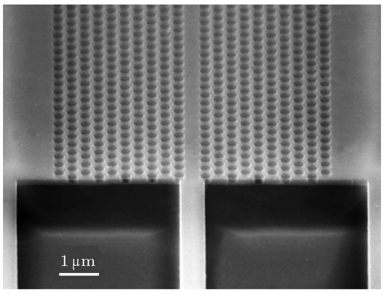

Fig. 2. SEM image of a W1 PCWG with an air-bridge structure.

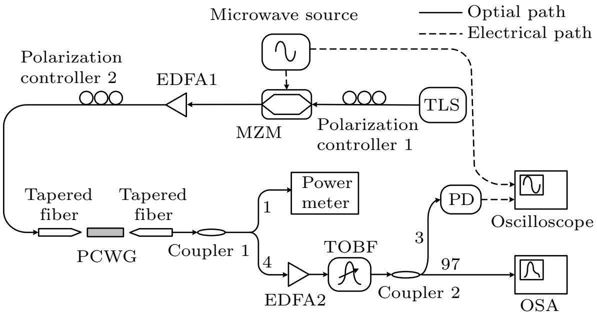

Fig. 3. Schematic diagram of the group delay measurement setup. TLS: tunable laser source. MZM: Mach–Zehnder modulator. EDFA: erbium doped fiber amplifier. TOBF: tunable optical band-pass filter. PD: photodetector. OSA: optical spectrum analyzer.

The measurement setup for optical TTD is shown in Fig. 3. Optical output of a tunable laser source (TLS, Santec TLS-210VF) was sinusoidally modulated by a 10-GHz microwave signal through a $LiNbO_3$ Mach–Zehnder modulator (MZM) and then amplified by an erbium doped fiber amplifier (EDFA) to improve the input power level. A polarization controller was used to adjust the polarization of optical signal as TE polarized state. The optical signal was coupled into and out of the PCWG by the end-fire method employing two tapered fibers and the output of the PCWG was separated through a 20/80 fiber coupler (coupler 1). Light in the 20% port was used to monitor the output power of the PCWG, while light in the 80% port was amplified through a second EDFA to compensate for the insertion loss of the device and filtered by a tunable optical band-pass filter (TOBF) to eliminate the amplified spontaneous emission (ASE) noise of the EDFA. The output of the TOBF was then branched into two by a 3/97 fiber coupler (coupler 2). An optical spectrum analyzer (OSA, Ando AQ6317) was used to measure the spectrum of the output signal in the 97% port and a PIN diode with a bandwidth of 50 GHz (u^2t Photonics, XPDV2120R) was used to demodulate the 10 GHz microwave signal in the 3% port. The demodulated signal was detected and displayed on a true time high-speed oscilloscope with a bandwidth of 14 GHz (Agilent DSO81204B) referenced by the modulating microwave signal. By detecting the phase shifts between the demodulated signals at different wavelengths, the spectral dependence of the delay time of the signal can be deduced.

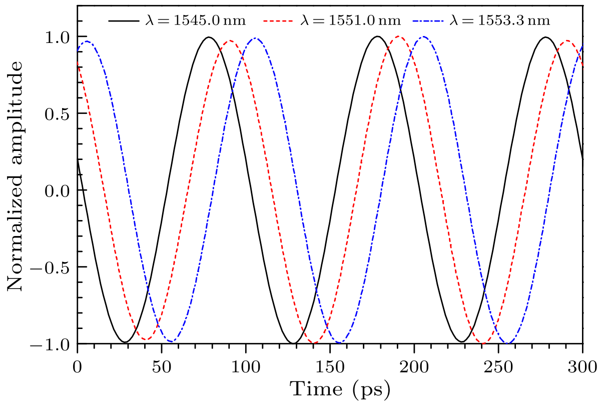

Fig. 4. Normalized output waveforms of the 10 GHz sinusoidal signal under different wavelengths.

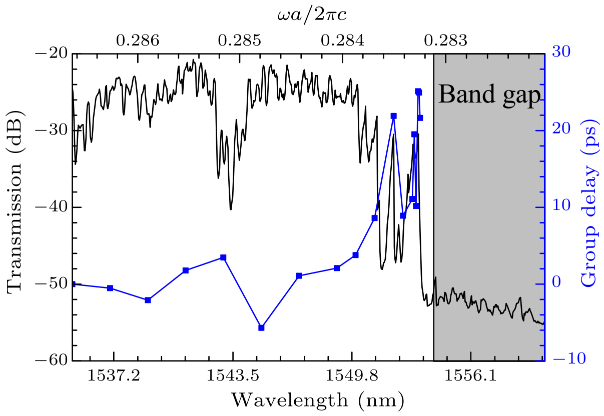

Fig. 5. Measured transmission and group delay spectra of the PCWG. Black line: transmission. Blue line with square symbol: group delay. The white and dark areas denote the wavelength ranges of the defect mode and band gap, respectively.

Figure 4 shows the normalized output waveforms of 10 GHz microwave signals at different optical carrier wavelengths. The phase shifts caused by slow light effect can be recognized clearly and no evident waveform distortion is observed. To evaluate the group delay accurately, we need to exclude the influence of second-order dispersion of the fibers in the system. By replacing the PCWG with a Si strip waveguide of the same length, we determined that the whole measurement system (without the PCWG) gave rise to a wavelength-dependent delay of about −0.4 ps/nm by linear fitting the measured results caused by the dispersion of the fiber and the Si strip waveguide. We also estimated that the variance of delay time caused by the fluctuation of the output power is below 2.5 ps, which is small enough to be neglected when the group velocity becomes lower.

The modified result of group delay caused by the PCWG is shown in Fig. 5 in blue line, together with the transmission spectrum. The calculated wavelength ranges of the defect mode and band gap are denoted by white and dark areas, respectively. It can be seen that, in agreement with the simulation results, the group delay increases as the optical carrier wavelength approaches the band edge ($\omega a/2\pi c = 0.281$ or $\lambda = 1554\,\mathrm{nm}$), indicating a lower group velocity. Although there are some fluctuations in both the transmission and group delay spectra, which can be considered as the influence of the disorders and nonuniformity introduced during the fabrication process,[15] a maximum group delay of 25 ps was achieved, corresponding to $\pi/2$ phase shift of the 10 GHz microwave signal. To evaluate the group index n_g $(= c/v_g)$, the PCWG is considered to reach a constant group index of about 10 when $\lambda < 1535\,\mathrm{nm}$, according to theoretical results.[16] Therefore, in the wavelength range of the defect mode, the group index of the PCWG is expressed as

$$n_g = \frac{\tau c}{l} + 10, \tag{1}$$

where τ is the group delay and l is the length of the PCWG. A maximum group index of 25 is evaluated based on the above analysis. A larger group delay was not obtained because the output signal became too weak to be detected when the carrier wavelength exceeded 1553.4 nm. By improving the fabrication techniques, a larger group delay is expected to be achieved in the future.

In conclusion, we have fabricated a 475-μm-long air-bridge PCWG and measured the optical TTD caused by the slow light effect. A wavelength-dependent group delay of 10 GHz sinusoidal microwave signal up to 25 ± 2.5 ps has been demonstrated, corresponding to slow light with a group velocity lower than $c/25$.

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