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New Design of All-Optical Slow Light TDM Structure Based on Photonic Crystals

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Abstract—This work demonstrates an all-optical slow light Time Division Multiplexing (TDM) structure based on photonic crystals (PCs). The structure shows good ability of dividing time domain signal into repetition time slots signal by four tunable group velocity waveguides from $0.006 * c$ to $0.248 * c$ where c is the velocity of light in the vacuum at the center wavelength of 1550 nm and over a bandwidth 4.52 THz with group velocity dispersion below $10^2\,\mathrm{ps}^2/\mathrm{km}$. New high efficiency Y-type directional coupling output can get larger than ∼1.4 times intensity and ∼93% loss improvement which are comparable to conventional output device. The proposed PCs waveguide structure is leading the way to achieve the TDM application and has good capability to extend the application of the optical communication and optical fiber sensors systems.

1. INTRODUCTION

Photonic crystals have become a popular research topic of worldwide interest. In 1987, Yablonovitch [1] and John [2] initially proposed the idea that a periodic dielectric structure can provide the property of band gap in certain regions of the frequency spectrum, similar to an electronic band gap existing in semiconductor materials. PCs are nano-structured material in which periodic dielectric variation structure results in a photonic band gap. Photonic crystal structure provides a method to control photons or, in general, electromagnetic waves in dielectric medium. Photons cannot travel through the crystal within this gap in certain regions of wavelengths or energies. This means that the capability of controlling photons can be obtained by introducing defects in PCs. In addition, we can use this concept to design waveguide by using PCs structure without the disadvantage of bending loss in conventional waveguide. One of the photonic crystal waveguides (PCW) is coupled cavity waveguide (CCW) [3, 4], consisting of a chain of high-Q optical cavities embedded in a PC. Light propagation in CCWs can be explained as photon hopping between nearby cavities as a result of overlapping of tightly confined modes. Unlike other types of optical waveguides, light in a CCW propagates with small group velocity in the defect chain. The coupling strength between neighboring cavities directly affects the dispersion and the group velocity of the guided modes [5–7]. In addition, another important property of CCW is that it is very efficient in guiding and bending of light. Due to interactions between neighboring cavity modes, light will be tightly confined at each defect. As previously described advantages, we use CCW to design this TDM structure.

In the field of optical communication and optical fiber sensor applications, a number of different sensors multiplexing have been reported and widely used [8–11], such as Time-Division-Multiplexing (TDM), Wavelength-Division-Multiplexing (WDM), Frequency-Division-Multiplexing (FDM) and Coherence-Division-Multiplexing (CDM). TDM system has been shown to have many advantages, such as low crosstalk and high sensitivity [12, 13], and the system also provides a easier and more useful

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mean of multiplexing technology. In the multiplexing system, TDM system can transfer multiple signals simultaneously as sub-channels in one communication channel of the same transmission media such as wires or fiber optics. The TDM system is treated as repetition light source module, which was gated by the amplitude modulator of an optical guide wave device (OGW) and a pulse generator. Through the TDM repetition light source module system, single light source system can have several recurrent time slots and carry signals to connect with array optical sensors for multiplexing technology utilization. TDM system is more cost effective due to single light source. It is capable of carrying multiple signals to array sensors as well as carrying signals back to detector with simple coding de-modulation method to get each sensor's information in same transmission media. In this paper, we will propose a new approach of TDM repetition light source module based on photonic crystal waveguide structures. The proposed TDM device designed by photonic crystal technology is at micrometer scale. The compact size of all-optical devices based on PCs waveguide structure can be fabricated by semiconductor process technology and easy to be realized by current process.

2. TIME-DIVISION-MULTIPLEXER (TDM) SYSTEM DESIGN MODELING

The group velocity V_g and group velocity dispersion (GVD) parameter β_2 of light with frequencies and wavenumbers k in an optical waveguide can be written as [14–16]:

$$V_g = \frac{d\omega}{dk} = \frac{c_0}{n_g} \tag{1}$$

$$\beta_2 = \frac{d^2k}{d\omega^2} = \frac{dn_g}{d\omega}\frac{1}{c_0} \tag{2}$$

where c_0 is the velocity of light in the vacuum and n_g the group index. Photonic crystal waveguide (PCW) application with slow light properties have been widely discussed [16–26] in the recent years. Slow light becomes possible to control the speed of light and can be applied to a great variety of applications, such as delay lines that control the arrival of optical signals and optical buffers. In order to obtain the desired slow-mode group velocity in the planar type photonic crystal structures, we designed a photonic crystal waveguide by CCW with cylinder silicon pillars by triangle structure in air, as shown in Figure 1.

As shown in Figure 2, the values of parameters were chosen as: $r_1 = 0.165 * a$, $r_2 = 0$, and $r_3 = 0.054 * a$, where a is the lattice constant. The relationship between group velocity V_g and wavenumbers k is shown in Eq. (1). Figure 3 shows that the dynamic group velocity tuning with different wavenumbers or frequencies is feasible. Frandsen et al. [16] also showed that perturbing the hole adjacent can increase the waveguide bandwidth by changing the hole size of the first two rows. As shown in Figure 4, we can get the relation between the group velocity and the normalized frequency by changing r_1 and r_2, respectively. Figure 4(a) shows that when r_1 increases, the peak of group velocity will also increase and accompany lower normalized frequency at the same time. And Figure 4(b) shows that when r_2 increases, the peak of group velocity will decrease and accompany higher normalized frequency. Consequently, the desired group velocity in the waveguide with the same normalized frequency 0.4228

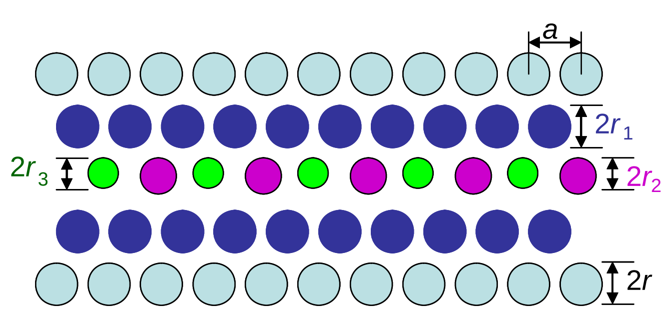


Figure 1. Schematic of the CCW in PCs, a and r represent the lattice constant and radius of line defect rods, respectively.

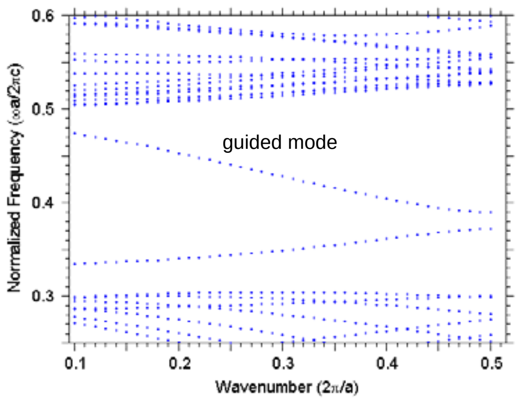


Figure 2. Schematic of photonic crystal band diagram.

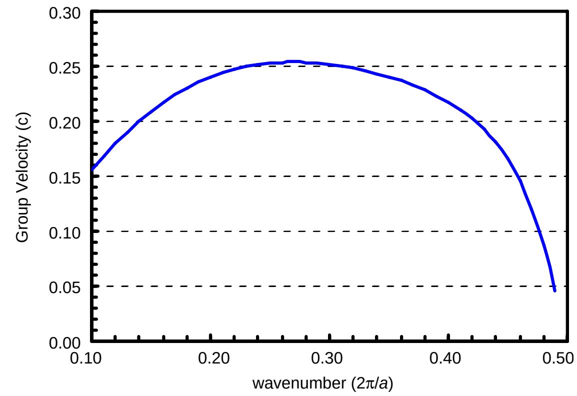
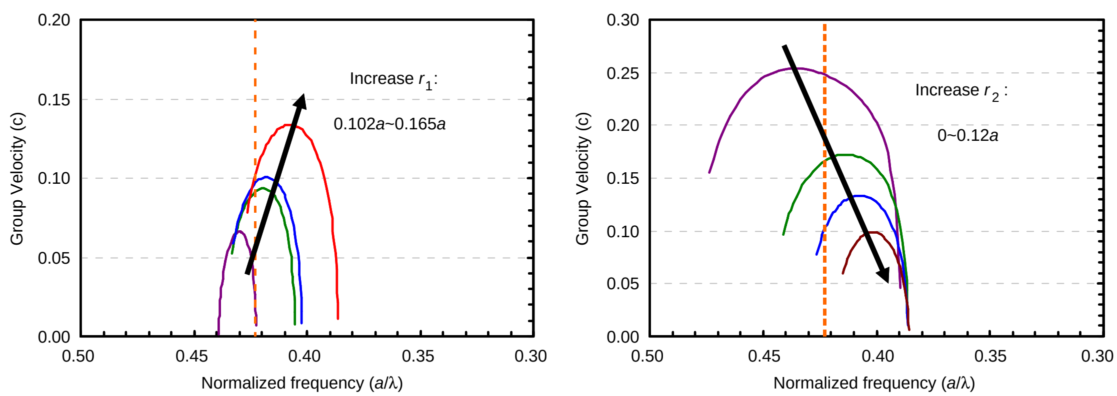


Figure 3. Schematic of group velocity V_g versus wavenumber.



(a) (b)

Figure 4. The relation between the group velocity and the normalized frequency for (a) r_1: $0.102a{\sim}0.165a$, (b) r_2: $0{\sim}0.12a$.

(center wavelength 1550 nm) can be selected to generate TDM pulse repetition function by using slow light phenomenon.

3. THE DESIGN OF MULTI-CHANNEL TIME-DIVISION-MULTIPLEXING (TDM) SYSTEM

In this paper, a novel all-optical slow-light TDM based on PCs waveguide structure with dynamic group velocity control is proposed, as shown in Figure 5. In this PCs system, high refractive index pillars with triangle lattice structure in air are used. The refractive index of silicon rod is 3.4 for an incident

Table 1. The r/a ratio of each CCW channel waveguide in the group velocity tuning area.

Channel	r/a ratio of each channel		
	r_1/a	r_2/a	r_3/a
CH1	0.165	0	0.054
CH2	0.130	0.08	0.054
CH3	0.125	0.1	0.054
CH4	0.102	0.1	0.054

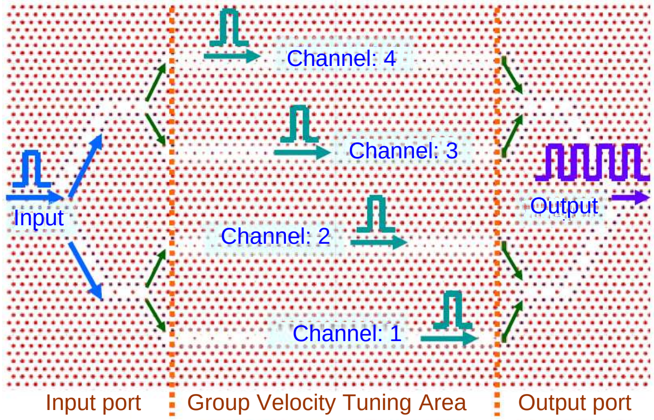


Figure 5. The schematic of TDM repetition light source module by PCs.

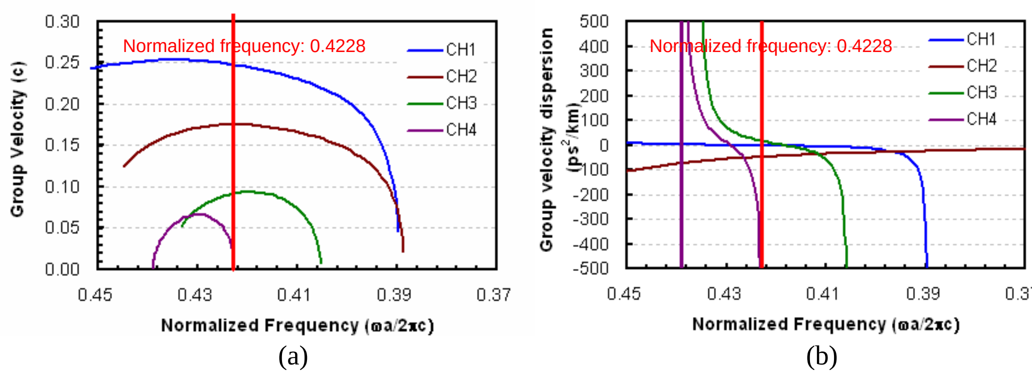


Figure 6. (a) The group velocity of each channels and (b) the group velocity dispersion of each channels with varying normalized frequency, the normalized frequency 0.4228 is for wavelength 1550 nm.

Table 2. Summary of each channel group velocity, propagation time to arrive output port at wavelength 1550 nm and bandwidth of Group Velocity Dispersion in the range of 10^2 ps^2/km.

Channel	Group velocity (c)	Propagation time (ps)	Bandwidth ($\Delta\omega/2\pi$) of Group Velocity Dispersion in the range of 10^2 ps^2/km
CH1	0.248	514	$>$ 38.93 THz
CH2	0.173	563	$>$ 25.78 THz
CH3	0.091	684	$>$ 10.71 THz
CH4	0.006	824	$>$ 4.52 THz

wavelength at 1550 nm with different r/a ratio (r: the radius of rod; a: the lattice constant). The silicon rod r/a ratio is 0.171, and the input/out port r/a ratio is 0.15. Table 1 shows the detailed r/a ratio description of each CCW channel waveguide in the group velocity tuning area. The extended mode and defect modes of the TM-polarization (the electric filed parallels the rod axis) band gap are calculated by the plan wave expansion (PWE) method. By using the results shown in Figure 4, different group velocity regimes can be selected to design the channel by perturbing the hole adjacent. The center wavelength of the light is 1550 nm with normalized frequency 0.4228 in this structure. At the normalized frequency 0.4228, we can get different group velocities and group velocity dispersions for each waveguide as shown in Figure 6. The Two-Dimension Finite-Difference-Time-Domain (2-D FDTD) method was performed

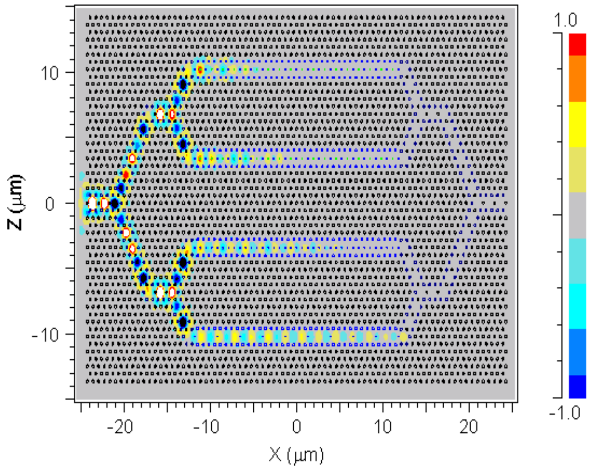


Figure 7. The FDTD simulated results of the steady-state electric field distributions at wavelength 1550 nm.

for simulation and showed good ability in forming TDM time slots output by each channel time delay behavior as shown in Figure 7. As summarized in Table 2, good results are obtained in terms of splitting the incident pulse into four spectral channels which have over a bandwidth 4.52 THz with group velocity dispersion below 10^2 ps^2/km and group velocity from $0.006 * c$ to $0.248 * c$ at center wavelength 1550 nm. The lead time of each channel output wave which arrives the output port can be separated from 514 ps to 824 ps to perform as TDM time repetition slots function in the output. The signals in each channel reach the output port with different time divisions, respectively. It implies that the time domain signals can be divided into several recurrent time slots effectively in this TDM repetition light source module.

4. NEW APPROACH OF HIGH-EFFICIENCY I/O OUTPUT PORT BASED ON DIRECTIONAL COUPLING DESIGN

A confluence Y-type structure is necessary at the conventional I/O device output end when the device is designed by using the I/O waveguides. Unfortunately, this type of device suffers high Insertion Loss (IL) and worse Directivity (DI) due to other input ports which will act as a splitter at the output side. As shown in Figure 8, if the signal is launched from Port A channel, the transmission loss of Port B (DI ∼2.37 dB) is about 51% and only ∼41% transmission could translate to the real output port (IL ∼3.87 dB), as shown in Table 3.

Table 3. Transmission of conventional Y-type output port when signal input form Port_A.

Transmission Intensity	**Output**	**Port_B**	**Port_A -> Output IL (dB)**	**Port_A -> Port_B DI (dB)**
Input from Port_A	41%	58%	3.87	2.37

Table 4. Transmission of new Y-type design ($L_a = 18a$, $L_b = 19a$).

Transmission Intensity	**Port_A**	**Port_B**	**Output**	**Port_A, B -> Output IL (dB)**	**Port_A,B -> Port_B, A DI (dB)**
Input from Port_A	-	3%	81%	0.92	15.23
Input from Port_B	2%	-	85.3%	2.34	16.99

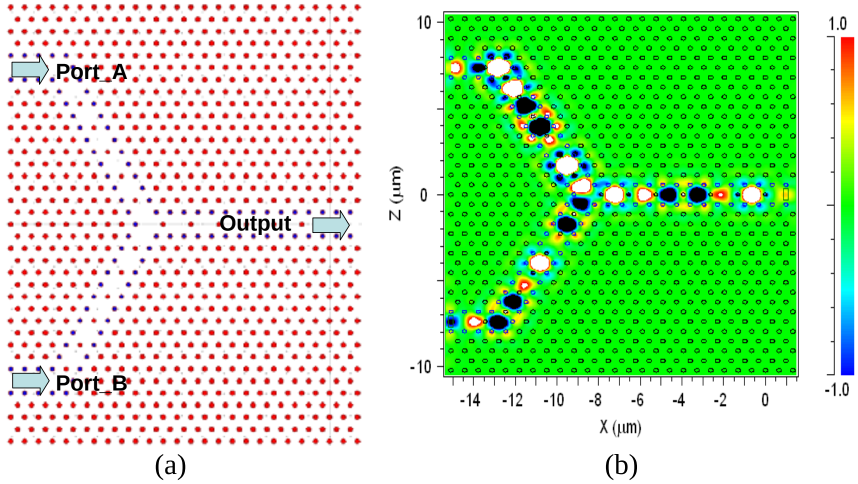


Figure 8. (a) Conventional Y-type output port design. (b) The steady-state electric field distributions of Y-type device for input side is Port_A, undesired loss was found art Port_B.

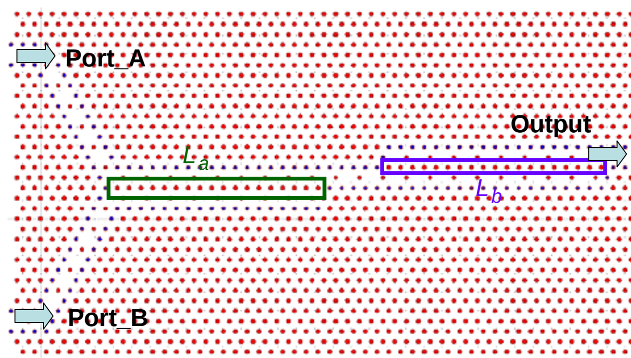


Figure 9. Schematic of a new high-efficiency Y-type output port design by directional coupling.

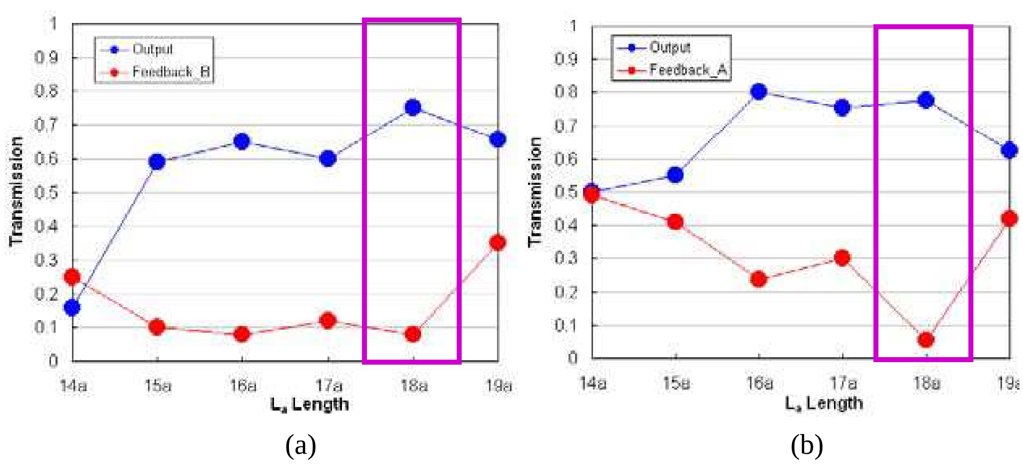


Figure 10. Normalized transmission at wavelength 1550 nm versus different coupling lengths with fix $L_b = 9a$ for (a) input from Port_A, (b) input from Port_B. The optimized coupling length is $18a$.

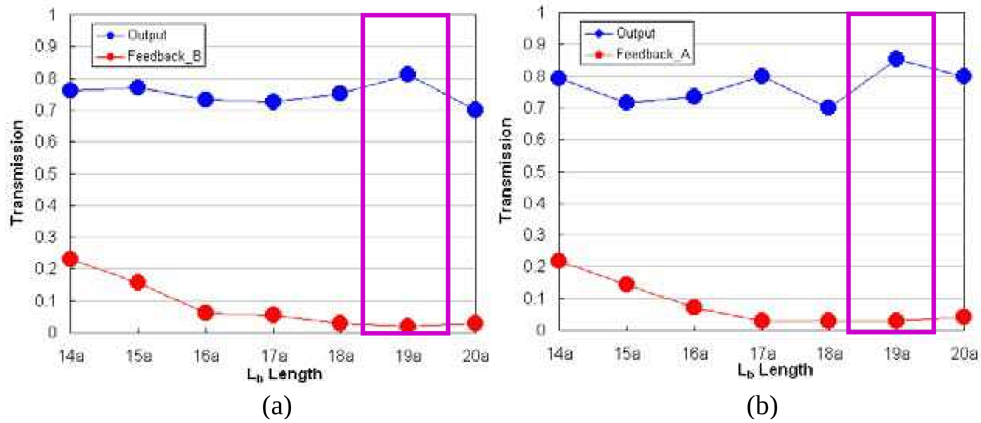


Figure 11. Normalized transmission at wavelength 1550 nm versus different coupling lengths with optimized coupling length $L_a = 18a$ for (a) input from Port_A, (b) input from Port_B. The optimized coupling length L_b is $19a$.

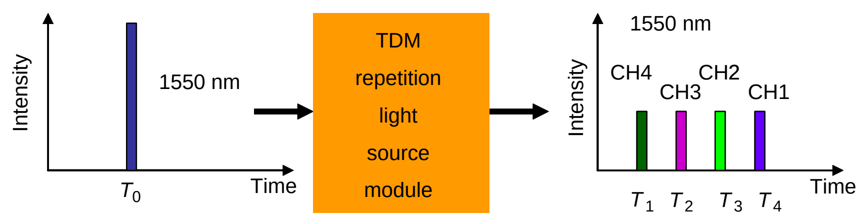


Figure 12. Schematic for four channels TDM system. The recurrent time slots function by four pulse channels with different group velocity selections of light at 1550 nm for TDM system.

In order to get higher transmission efficiency, a new approach of Y-type structure which is optimized by directional coupling based on PC waveguide directional coupler idea was proposed. The new Y-type directional coupling output port consists of three parallel line-defect waveguides with two 45 degree separated input ports is shown in Figure 9. In this work, the new Y-type directional coupling output port can demonstrate high transmission efficiency and low feedback to the other input port by optimized waveguide length L_a and L_b. As shown in Figures 10 and 11, the optimized waveguide length L_a is $18a$, and length L_b is $19a$ for both Ports A and B in which the transmission efficiency with low loss performance can be obtained. The good results are shown in Table 4. The transmission loss is less than 3% (DI ∼15.23 dB) and the transmission efficiency of the output port greater than 81% (IL ∼0.92 dB). Comparing with above device design, we can get larger than ∼1.4 times (from 58% to 81%) intensity and ∼93% loss (from 41% to 3%) improvement with the simple structure design. Based on the proposed TDM PCs waveguide structure, we can get recurrent time slots function by four pulse channels with different group velocity selections of light at 1550 nm for TDM system as shown in Figure 12. As the result, the time domain signals can be realized and divided into several recurrent time slots effectively in this TDM system. The compact (micrometer scale) and simple structure is useful for integrating optical circuit realization and future device fabrication.

5. CONCLUSION

In this paper, an all-optical slow light TDM structure based on PCs is successfully proposed. It shows good ability of TDM recurrent time slots function by four pulse channels with different group velocity selections from $0.006 * c$ to $0.248 * c$ and over a bandwidth 4.52 THz with the group velocity dispersion (GVD) below $10^2\,\mathrm{ps^2/km}$. In addition, the lead time of each channel output wave which arrives the output port can be separated from 514 ps to 824 ps to perform as TDM time repetition slots function in the output port at wavelength 1550 nm. The new Y-type output port with direction coupling design can get larger than ∼1.4 times intensity and ∼93% loss improvement which are comparable to conventional I/O Y-type confluence device. The proposed all-optical slow light waveguide structure will lead the way to TDM application. It has good capability of extending the application to the optical communication and the optical sensor field. It is also expandable to combine with WDM system as huge array multiplexing system. The compact and simple structures in PCs base are the main advantages of this TDM design. It can also be easily realized by current advanced lithography technology like 20 nm node for the thin rod (few tens of nanometers) process. Consequently, such kinds of devices will be more useful for integrating optics circuit realization and future device fabrication.

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