Slow-Light performance enhancement of delay line based on arced photonic crystal waveguide

Zaineb Gharsallah
ESPRIT School of Engineering, Tunis. Tunisia
University of Tunis El Manar, National Engineering School of Tunis,
Communications Systems Lab (LRSys'Com-ENIT), LR-99-ES21 1002, Tunis, Tunisia
gharsallah.zaineb@hotmail.fr

Radhouene Massoudi
ESPRIT School of Engineering, Tunis. Tunisia
University of Tunis El Manar, National Engineering School of Tunis,
Communications Systems Lab (LRSys'Com-ENIT), LR-99-ES21 1002, Tunis, Tunisia
massoudiradhouene@hotmail.com

Monia Najjar
University of Tunis El Manar,
Higher Institute of Computer, 2080
Ariana, Tunisia
monianajjar@yahoo.fr

Bhuvneshwer Suthar
Department of Physics,
M.L.B. Govt. College, Nokha 334803,
Rajasthan, India
bhuvneshwer@gmail.com

***Abstract*—In the present paper, we proposed a slow light structure using arced photonic crystal waveguide (PhCW) to design an optical delay line. A delay bandwidth product value is calculated by comparing the arced PhCW with a straight PhCW. It's seen that the arced PhCW offers a very simple method to slow down the light speed with a bandwidth of 294 THz and a delay bandwidth product of 32.34. An average group index equals to 13 is demonstrated which yield to 110 fs delay time for a device footprint of 14 x 19 μm 2 . The signal shape is notably maintained constant over the proposed delay line. Furthermore, the suggested device is characterized by a small dispersion which leads to a slight group-velocity dispersion.**

***Index Terms*—Photonic crystal; arced waveguide; straight waveguide; slow light; delay line**

I. Introduction

Optical fiber is commonly used to achieve large delay due to many properties such as its very low loss propagation and its large bandwidth. Even so, this sort of delay lines based on optical fibers need overlong optical fibers and it can't easily integrated with photonic crystal devices [1]. Optical delay lines basing on the philosophy of slow light with a notably very low group velocity are indispensable for advanced time domain optical signal processing at network nodes in future optical communication systems [2]–[4] . Various approaches were used to engender slow light like: Bragg fiber, Fabri Perot resonant cavity [5] , planar waveguide and photonic crystal waveguides [2]–[6]. Comparing with different methods and basing on theoretical and experimental analysis, it is concluded that photonic crystal waveguide is the best candidate to achieve slow light due to the large bandwidth, less losses, small size and ability to work at room temperature. Thus, Photonic crystal became very promising for controlling light propagation with the use of low group velocity (Vg). Therefore, a small Vg is beneficial because of its numerous applications in optical domain beyond delay lines such as buffers, enhancing nonlinearities and increasing light matter interaction [4], [7]–[9] . Many works has achieved slow light basing on straight PhCW joined with some modification including varying the width of the waveguide by modifying the placement of the air holes bordering the waveguide vertically or horizontally [10]–[13], adjusting the lattice constant of the rows bordering the waveguide [14] , altering the hole's radii or hole's form [2], [3], [6], [7] , filtering the holes bordering the waveguide with lower refractive index than slab index [15] and employing ring-shaped [16]. Consequently, these methods are accompanied with extremely large group-velocity dispersion (GVD) at the band edges which might distort transmitted pulses. To avoid this problem, others researches attained slow

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light using complex structures. We can mention in particular waveguide bends and waveguide coupled cavities [17]–[20] . According to fabrication processes, these methods need bigger structure size than previously proposed approaches [2], [4], [7], [10], [14], [15] and it's very hard to control the defect mode fabrication errors in such design. To get both advantages, slow light and simple photonic crystal structure waveguide, an arced waveguide is proposed in this work. A perfect slow light structure should has wide bandwidth and low high-order dispersion, which are essential and crucial for practical use of slow light. The present work exploits an arced form of PhCW to carry out slow light with a small size device and small dispersion. It consists of arced PhCW in cubic lattice with circular air holes in dielectric medium. Firstly, in section 2, we present the background and we explain the essential criteria of slow light. Then, in section3, we propose a method for guiding light over arced PhCW in order to reduce light velocity with a comparison to a straight PhCW. The results and discussions are provided in section 4. Structure dimension optimization is discussed in section 5. Finally, we conclude our work in section 6.

II. BACKGROUND AND SLOW LIGHT CRITERIA

As it's known that photonic crystal (PhC) is a design characterized by a periodic refractive index variation on the scale of nanometer. It can guide light basing on the principle of photonic band gap. Additionally, it is possible to obtain a small group velocity by setting the structure parameters to adjust the dispersion relation [2]. In this section, we shortly review the main terminologies of slow light. The total delay time τ over PhC structure length (L) is given by:

$$\tau = \int_0^L \frac{\mathrm{d}x}{Vg(x)} \tag{1}$$

Where Vg is the group velocity in PhC which is the main feature of slow light. The average group index ng characterizes the performance of delay line and it's written as:

$$\widehat{ng}(x) = C\frac{\Delta k}{\Delta\omega} = \int_{k0}^{k0+\Delta k} \frac{C\delta k}{\Delta\omega} = \int_{k0}^{k0+\Delta k} \frac{C\delta k\delta\omega}{\Delta\omega\delta\omega} \tag{2}$$

Then

$$\widehat{ng}(x) = \int_{\omega 0}^{\omega 0+\Delta\omega} n_g(\omega)\frac{\delta\omega}{\Delta\omega} \tag{3}$$

Where the frequency and the wavenumber are presented by ω and k, respectively. $\omega 0$ and k0 are the corresponding frequency and wavenumber at input point (x=0), while $\Delta\omega$ and Δk are their variation at x= ΔL. By considering the bandwidth shift for a given propagation distance ΔL, equation (3) can be expressed as:

$$\widehat{ng}(x) == \int_0^{\Delta L} n_g(x)\frac{\delta x}{\Delta L} = \frac{C.\tau}{\Delta L} \tag{4}$$

Equation (4) shows that ng depends not only of the frequencies but it depends on the signal form and its properties at start and end points. Slow light is usually accompanied by group velocity dispersion (GVD) which distort the signal shape. To overcome the GVD problem, we should inject a Gaussian pulse in the input of PhCW structure. This pulse is expressed as a Gaussian envelope function multiplied by a sinusoidal carrier (eq.5):

$$g(t) = sin(\frac{2\pi}{\lambda}(t) + At^2 + \varphi_0)e^{-(\frac{t}{t_1}-\tau)^2} \tag{5}$$

Where λ indicates the wavelength center, t1 is the input pulse time (μm) and τ is the delay time. The coefficient A, expressed by a unit of μm2, indicates the chirp coefficient. The phase constant φ0 is selected to be zero at the maximum of the Gaussian function. Optical bandwidth value can be given in term of frequency, wavelength and time. In view of the relation between bandwidth ($\delta\omega$) and wavelength bandwidth ($\Delta\lambda$), the conversion between them depends on the center of wavelength or the center of frequency. To convert from wavelength to frequency and vice versa, we use the following equation:

$$\delta t = \frac{2ln2}{\pi\delta\omega} = \frac{0.4413}{\delta\omega} \tag{6}$$

The mathematical description of the pulse envelope in equation (5) is conducted with variables in either the time g (t) or angular frequency g(ω) domain through a Fourier transform relationship [21]. The variables δt and $\delta\omega$ represent the full width at half maximum (FWHM) in the time domain and in the angular frequency domain, respectively. The relation between δ t and $\delta\omega$ is described as follows [22]:

$$\delta t = \frac{2ln2}{\pi\delta\omega} = \frac{0.4413}{\delta\omega} \tag{7}$$

III. ARCED WAVEGUIDE DESIGN AND NUMERICAL SIMULATION

In this work, we propose a PhC structure based on a cubic lattice with circular air holes in dielectric medium of refractive index equals to 3.46 (silicon). The operating wavelength is 1.55 μm. So, to get a large band gap the radius of air holes "r" is equal 0.4a where "a" is the lattice constant which is equal to 0.64 µm. These parameters are used to design, at first, a straight PhCW with only one line default with a total length L1= 28a, secondly, the arced PhCW to be used as a delay line. Therefore, the arced PhCW consists of two vertical waveguides joined to a half-circle waveguide. The half circle is designed with fixing the x position using the function cosine and the z position using sine function. Also, we fix the number of rows on right and left sides of waveguide being 6 rows to reduce the losses [23].

In the arced PhCW, the light is delayed by enlarging the followed path by the light (L2=40a) compared to straight PhCW and by restraining the velocity through the use of the curvature form. The radius of the outer holes and inner holes bordering the arced PhCW, presented by blue and yellow color in "Fig. 1-b", are indicated by r1 and r2, respectivily. Initially, these radii have the same values as the straight PhCW. The

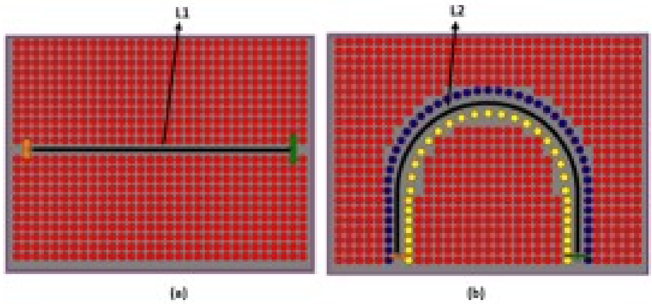

Fig. 1. Schematic view of (a) straight PhCW (b) arced PhCW

purpose of this work is to calculate the time delay by comparing the propagation time through arced PhCW and straight PhCW in two cases: firstly for same structures footprint and secondly for same path length L1.

IV. RESULTS AND DISCUSSION

To analyze the above structures, a Gaussian pulse of 2 fs width (FHWM) is injected into both PhCW structures “Fig. 2”.

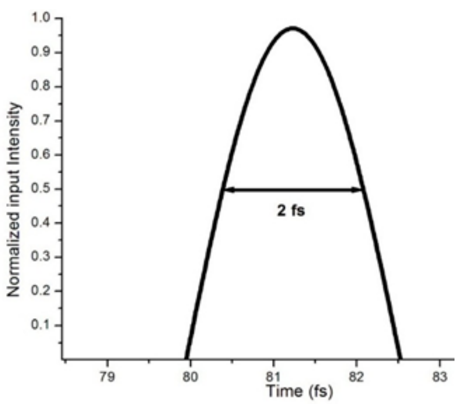

Fig. 2. Normalized intensity of input pulse

“Fig. 3-a” indicates the normalized output intensity of the straight PhCW. We investigate the pulse propagating through the PhCW to conclude that the intensity of output signal don’t suffer serious attenuation (0.88). Furthermore, the width of output optical pulse is kept the same as the input signal and no broadening is observed. On the contrary, the output normalized intensity of the arced PhCW is reduced to 0.60 and its width (FWHM) is compressed to 1.7fs. This compression is due to GVD dispersion in slow light medium which leads to waveform change [24], [25].

The output intensity of arced PhCW is less than the minimum required intensity for practical applications. Therefore, it’s very necessary to optimize the arced PhCW performances, by investigating the radii variation of outer and inner holes basing on the work discussed in [3], [6]. Firstly, we fix r2 to its initial values (r2= 0.40a) and we vary r1 from 0.49a to 0.18a (“Fig. 4”). From the above curve, as r1 increases the

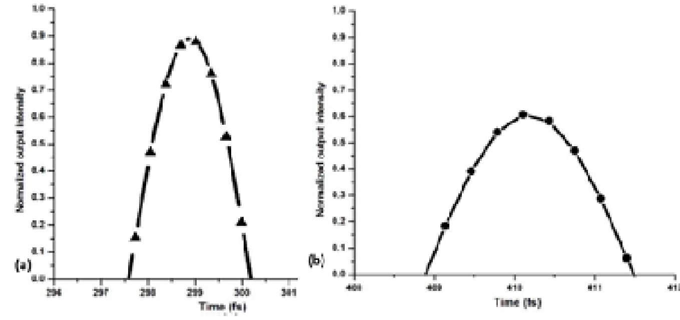

Fig. 3. Output normalized intensity for (a) straight PhCW (b) arced PhCW

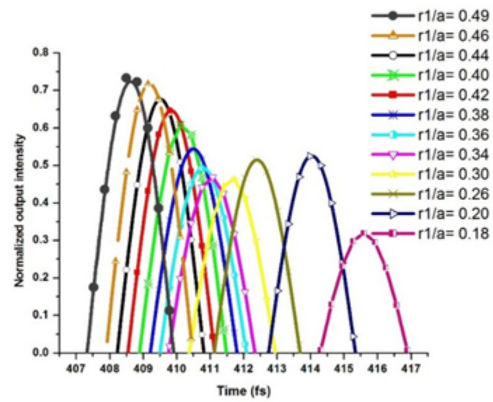

Fig. 4. Output normalized intensity for different values of outer radius r1

output intensity, the delay time and the group index increase also. The increase of output intensity can be explained by the loss decrease due increasing of outer holes. When we vary r1, slow light phenomena takes place in arced waveguide. Hence a decrease of group velocity can be seen which explains these increase of delay time and group index. Therefore and due to practical aspect the radius should be limited by 0.5a accordingly the maximum value of r1 is 049a where the maximum output intensity is reached. The detailed specifications of the normalized output intensity for different values of r1 are listed in table1.

For further performance assessment of arced PhCW, we fix the value of r1 that corresponding to the maximum output intensity (r1=0.49a) and we vary the radius r2 from 0.49a to 0.26a. The results are presented in next figure. From “Fig. 5”, we note that when we increase r2, the delay time and the group index increase whereas the normalized output intensity first increases then decreases. It reaches its maximum when r2 is equal to 0.38a (solid diamond symbol). The detailed specifications of the output intensities for different values of r2 are resumed in table2.

The parameters r1 and r2 characterizing the arced structure have remarkable effect on the properties of output intensity and delay time. The increase of the normalized output intensity is explained by the fact that the photonic band gap (PBG)

TABLE I
NORMALIZED OUTPUT INTENSITY AND DELAY TIME FOR DIFFERENT VALUES OF OUTER RADIUS R1

r1	*Normalized Output intensity*	*Delay time (fs)*	*ng*
0.49 a	0.73	327.1	12.84375
0.46 a	0.702	327.7	12.91406
0.44 a	0.67	328	12.94922
0.42 a	0.64	328.3	12.98438
0.40 a	0.60	328.7	13.03125
0.38 a	0.54	329	13.06641
0.36 a	0.48	329.3	13.10156
0.34 a	0.47	329.6	13.13672
0.30 a	0.52	330.2	13.20703
0.26 a	0.52	331	13.30078
0.20 a	0.53	332.5	13.47656
0.18 a	0.34	334.1	13.66406

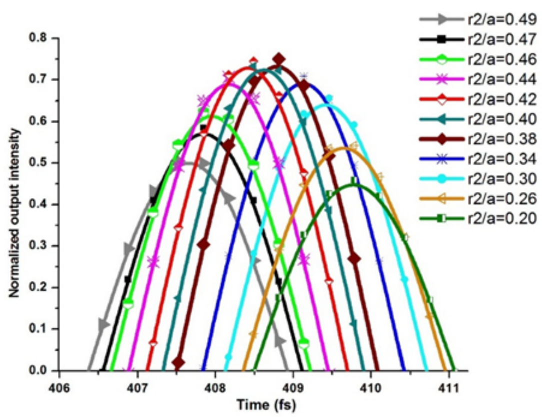

Fig. 5. Output normalized intensity for different values of inner radius r2

TABLE II
NORMALIZED OUTPUT INTENSITY AND DELAY TIME FOR DIFFERENT VALUES OF INNER RADIUS R2

r2	*Normalized Output intensity*	*Delay time (fs)*	*ng*
0.49 a	0.5	326	12.71484
0.47 a	0.57	326.1	12.72656
0.46 a	0.61	326.3	12.75
0.44 a	0.67	326.5	12.77344
0.42 a	0.64	326.8	12.80859
0.40 a	0.60	327.1	12.84375
0.38 a	0.54	327.5	12.89063
0.34 a	0.47	327.7	12.91406
0.30 a	0.52	327.9	12.9375
0.26 a	0.52	328.2	12.97266
0.20 a	0.53	328.3	12.98438

dependent on both radius which affect the output intensity. The increase of delay time shows explicitly that the outer and inner rows of holes of the arced PhCW is of critical importance for the slow-light regime. Thus, the structure is further analyzed for the highest value of output intensity (0.74) which corresponds to r1= 0.49a and r2= 0.38a.

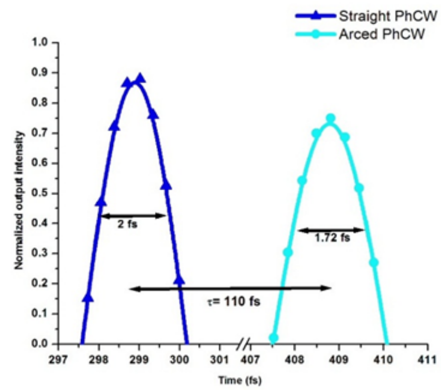

Fig. 6. Output normalized intensity of PhCWs for an input pulse width of 2fs

"Fig. 6" represents the output pulse for Straight PhCW (up triangle symbol) and arced PhCW (solid circle symbol). As it can be noted for both proposed structures, the normalized pulse amplitude is reduced to 0.88 and to 0.74 for straight PhCW and arced PhCW, respectively. The total time taken by the main lobe peak to reach the output of straight PhCW is approximately 217.5 fs. Otherwise, it takes 327.5 fs to cross the arced PhCW. Accordingly, the arced PhCW plays the role of delay line with delay time taux=110 fs. By applying equation (6), we calculate the value of the bandwidth (deltaomega) and the delay bandwidth product which are 256.5 THz and 28.21, respectively. To our knowledge, this is among the largest product time-bandwidth compared to several published results. In order to investigation the pulse width, we injected into the PhCW a Gaussian femtosecond pulses with different input times width (from 0.25 fs to 6 fs). The delay time and output intensities on the function of input time width are shown in "Fig. 7".

We can observe that for input time lower than 1.5 fs, the output intensities are very weak. Even so the delay time is significant, the minimum input time should be equal to 1.5 fs which leads to conclude that the highest operation bandwidth that we can employ for this structure is 294 THz. The delay-bandwidth product in this case is equal to 32.34. Furthermore, the operation bandwidth of previously reported works based on PhC is around hundreds of gigahertz at most, so larger operation bandwidth in excess of 100 THz PhC based devices has not yet been achieved according to our knowledge.

V. STRUCTURE DIMENSION OPTIMIZATION

In order to optimize the dimension of arced PhCW by 35% "Fig. 10", we keep the same path length L1 of straight PhCW.

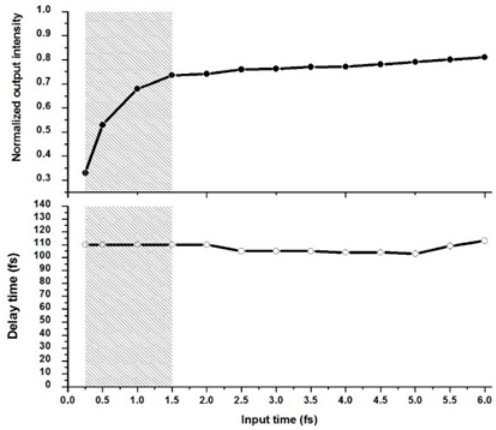

Fig. 7. Delay time and normalized output intensity as a function of input time width

As a result, the normalized output intensity is reduced (0.65) which requires an important parameters optimization.

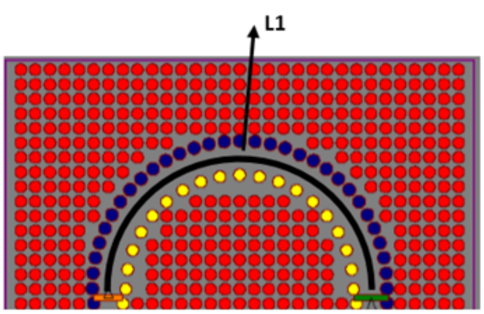

Fig. 8. Schematic view of optimized arced structure

Same simulations are reproduced as previous section, the radii r2 and r1 are varied from 0.49a to 0.10a to obtain the best normalized output intensity of the structure. The optimized value of r1 and r2 are 0.42a and 0.20a, respectively. “Fig. 9” represents the output intensity of Straight PhCW (up triangle symbol) and arced PhCW (solid circle symbol). It can be observed for both proposed PhCW forms, the normalized intensity of injected pulse is reduced to 0.88 and 0.84 for straight PhCW and arced PhCW, respectively. In addition, a response delay line of taux1=20 fs for the straight and arced PhCW is noted.

To study the light delay behavior in very high speed system, pulses with very short duration, in the order of femtoseconds, are lunched in the input of arced PhCW. The delay time and normalized output intensities are simulated and presented in “Fig. 10”. For input pulse duration vary from 0.25 fs to 6 fs, only the interval 0.75 fs - 2fs can be considered as it provides the highest delay time and the significant output intensities.

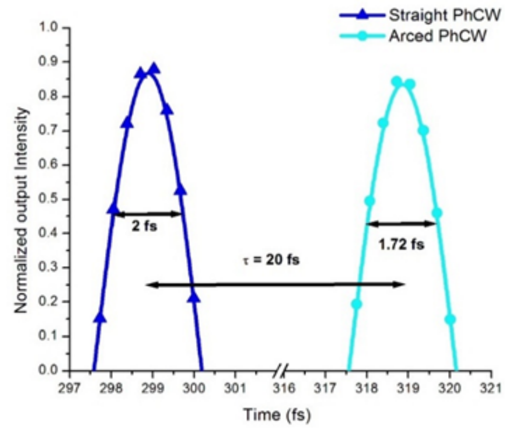

Fig. 9. Output optical pulse of straight and arced structure using an input pulse width of 2fs

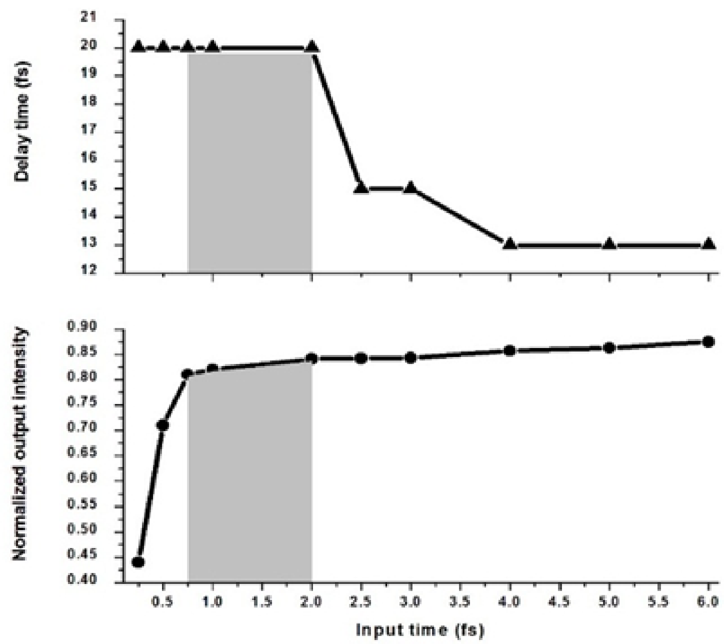

Fig. 10. Delay time and normalized output intensity as a function of different input pulse

VI. CONCLUSION

In this work, we developed a 14*19 µm2 PhC that can guide light through two different paths arced and straight PhCW. We showed that by making use of arced PhCW the light is delayed with a very small group velocity dispersion. By adjusting the radii of inner and outer holes bordering the waveguide, a maximum output intensity is obtained. Moreover, slow light is proved in this paper basing on time domain optical signal processing. This type of PhCW can be a most attracting device for slow light applications precisely optical buffer design, all optical switching and for improving light matter interaction in linear and nonlinear structure.

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