Optik 125 (2014) 3081–3084

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Nonlinear performance in silicon nitride slow light photonic crystal waveguides with elliptical holes

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ARTICLE INFO

Article history:
Received 23 June 2013
Accepted 15 December 2013

Keywords:
Photonic crystals
Elliptical holes
Group index
Silicon nitride
Slow down factor.

ABSTRACT

We propose a slow-light photonic crystal waveguide, which uses a combination of circular and elliptical air holes arranged in a hexagonal lattice with the background material of silicon nitride (refractive index $n = 2.06$). Large value of normalized delay bandwidth product (NDBP = 0.3708) is obtained. We have analyzed nonlinear performance of the structure. With our proposed geometry strong SPM is observed at moderate peak power levels. Proposed photonic crystal waveguide has slow light applications such as reduction in length and power consumption of all-optical and electro-optic switches at optical frequency.

1. Introduction

Photonic crystal (PhC) has many applications in the different field of technology. The concept of PhC structures was introduced about 25 years ago. This new technology offers lossless control of light propagation at very small scale in the order of the wavelength of light. There are many significant applications of Photonic crystal such as dispersion compensation photonic crystal fiber (DCPCF) [1], optical switches etc. In [2] optical switch based on nonlinear photonic crystal directional coupler has been simulated and analyzed by the finite difference time domain (FDTD) method. Zhang et al. proposed and analyzed a novel multi-way high efficiency composite beam splitter based on propagation properties of the light waves in directional coupler and Y-junction [3]. By providing a slow-light region using elliptical cells, a coupling length of just 2.58 μm is achieved at optical wavelength [4]. Slow light photonic crystal (PC) waveguides has attracted a great attention over recent years because it is compatible with on-chip integration and offer wide-bandwidth and dispersion-free propagation [5,6]. Recently Hao et al. has designed novel slow light waveguide with controllable delay bandwidth product and ultra-low dispersion by shifting the boundaries of waveguide. They have obtained constant group index n_g over large bandwidth with the normalized delay bandwidth product (NDBP) equal to 0.3141 [7]. Saynatjoki A. et al. have proposed photonic crystal waveguides with ring-shaped holes to minimize dispersion in the slow light regime. They have obtained average group index of 37 with 8 nm bandwidth [8]. Slow light mode have significant group velocity dispersion (GVD), which leads to optical signal degradation during pulse propagation hence, structural parameters of perfect crystal are tailored to achieve dispersion free slow light over the largest possible bandwidth [9]. Various structural tuning methods have been suggested in 2D-photonic crystals to achieve dispersion free slow light [7–12]. In our previous work we have proposed a deformed 2D photonic crystal waveguide by replacing two innermost rows of circular air holes with rows of elliptical air holes [13]. We have achieved a large value of normalized delay bandwidth product (NDBP) equal to 0.3745 that is 18% larger than previously reported its circular counterpart. In present work we have verified nonlinear performance of the photonic crystal waveguide, with utilizing highly nonlinear background medium i.e. silicon nitride. It has been observed that the enhancement of self-phase modulation (SPM) exhibited by photonic crystal waveguide designed with elliptic air holes defect is much stronger than its circular counterpart. To investigate nonlinear performance of photonic crystal waveguide, self-phase modulation has been explored in [14]. In their work, 80 μm long silicon PhC waveguide has been used to investigate SPM for group velocities range between c/20 to c/50. As well as, in their work the nonlinear enhancement of a slow light waveguide has been investigated by simply providing by its group index (n_g), in that case the group index (n_g) is nearly constant over bandwidth around 5 nm [14]. To improve nonlinear effects in periodic structure, interaction of the guided mode with the periodic lattice is important. This can be possible by maintaining group index (n_g) constant over on

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0030-4026/$ – see front matter © 2014 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2014.01.018

higher bandwidth. In our work bandwidth (nm) over which, group index (n_g) is nearly constant is 27.7 nm, for elliptical holes slow light waveguide and 11.78 nm for circular holes slow light waveguide. Rather providing nonlinear enhancement of a slow light waveguide by simply its group index (n_g), we consider here normalized delay-bandwidth product, which is more meaningful.

2. Background and structural analysis

Slow light in photonic crystals is defined as the velocity of light, which is larger than zero but less than that of phase velocity. In other words, it is the propagation of an optical pulse with very low group velocity [5]. The most important parameter to quantify the performance of slow light is 'Normalized delay-bandwidth product' (NDBP). It is used to define the capacity of the slow light device. NDBP is the product of average group index n_g and frequency range (bandwidth) over which n_g remains nearly constant. NDBP is given as [11]

$$\mathrm{NDBP} = n_g \times \left[\frac{\Delta\omega}{\omega_0}\right] \quad (1)$$

where $(\Delta\omega/\omega_0)$ is normalized bandwidth. The group index is assumed constant within ±10% variation of average group index n_g.

Inset Fig. 1(a), illustrates the schematic of the proposed design with two rows of elliptical air holes bordering the waveguide [13]. We denote this new design of slow light waveguide as the elliptical holes slow light waveguide (ESL). First and second rows of holes adjacent to the waveguide are also shifted vertically by s_1 and s_2 distance respectively. Direction of the shift s_1 is opposite to the direction of a shift s_2 as shown in inset Fig. 1. Optimized results have been obtained, when first row and second row of air holes are shifted vertically by distance $s_1 = -0.1$a and $s_2 = 0.085$a respectively [13], where 'a' is a lattice constant. Radius of basic circular holes that are away from the defect is 0.286a, and refractive index of silicon nitride as the background medium is $n = 2.06$. In fact the optimum values of the parameters obtained by us after several iterations. Only optimized results were included in the paper. For defect free photonic crystal, band-gap region extends from a normalized frequency range of 0.34 (ωa/2πc) to 0.39 (ωa/2πc) i.e. there is no longer allowed energy state within this frequency range. In Fig. 1(a), group index, n_g is plotted against normalized frequency for elliptical holes slow light waveguide and its circular counterpart i.e. circular holes slow light waveguide. In the circular hole slow light waveguide first row and second row of air holes are shifted vertically by distance $s_1 = -0.1$a and $s_2 = 0.085$a respectively as discussed in [13]. Radii of all circular holes are 0.286a, whereas photonic crystal waveguide with circular air holes, without any shifting of the rows is considered as reference waveguide or fast light waveguide. In Fig. 1(b), group index, n_g is plotted against wave-vector (k) for elliptical holes slow light waveguide, circular holes slow light waveguide and fast light waveguide. In Fig. 1(b), the Δk is defined as wave-vector of the flat dispersion curve for which group index remain constant within ±10% variation of average group index n_g. The value of Δk for elliptical holes slow light waveguide is from 0.36 to 0.45 and the value of Δk for circular holes slow light waveguide is from 0.38 to 0.42. The optimised values of the major and minor radii of the elliptical cells are shown in Table 1. The slow light performances between our geometry and previous published structures are shown in Table 2.

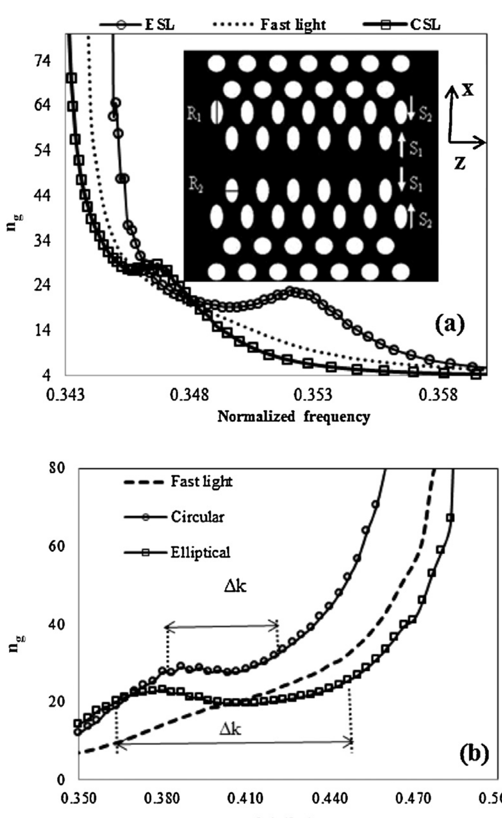

Fig. 1. (a) Group index as a function of normalized frequency. Inset shows the schematic of proposed structure (with two rows of elliptical air holes bordering the W1 waveguide) where arrows show the direction of shift s_1 and s_2. (b) Group index as a function of wave-vector k ($a/2\pi$), for elliptical hole slow light waveguide, circular hole slow light waveguide and fast light waveguide.

Table 1
Variation of group indices n_g and NDBP values obtained by tuning the axes (major axis R_1, minor axis R_2) for elliptical hole slow light waveguide (ESL) and circular hole slow light waveguide (CSL).

Waveguides	R_1/a	R_2/a	n_g	$\Delta\omega/\omega_0$	NDBP
ESL	0.395	0.206	20.87	0.0179	0.3745
CSL	0.286	0.286	28.29	0.0076	0.2153

3. Nonlinear performance

Self-phase modulation refers to the self-induced phase shift experienced by an optical field during its propagation in optical waveguide. It is responsible for spectral broadening of short pulses [15]. We utilized highly nonlinear silicon nitride. Silicon nitride is mostly used in high-endurance and high temperature applications, such as gas turbines, car engine parts, bio-sensing, etc. [16]. It is also compatible with standard complementary metal oxide semiconductor (CMOS) fabrication processes. Its Kerr coefficient, $n_2 = 2.4 \times 10^{-15}$ cm^2 W [16,17]. We perform FDTD analysis to investigate nonlinear performance of the structure. We observe, SPM induced broadening of pulse transmitted through a proposed nonlinear waveguide. An excitation pulse we employed is 1.55 μm wavelength. Fig. 2 displays evolution of output light spec-

Table 2
The slow light performances between our geometry and previous published structures.

Reference no.	n_g	Bandwidth at optical wavelength (nm)	NDBP
[12]	74.4	2.3	0.1104
[8]	37	8	0.1909
[10]	23	17.6	0.2611
[11]	44	11	0.3122
[7]	11	43.45	0.3141
In our work	31	18.52	0.3708