Fabrication of high efficiency compact 90° bend waveguide by using a dielectric 2D-PC structure

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ABSTRACT

In this paper we propose the design and the fabrication of 90° bend ridge waveguide (WG) assisted by a two-dimensional photonic crystal (2D-PC). 2D-PCs act as efficient mirrors along the boundaries of the bend ridge thus reducing the in-plane losses. The ridge waveguide consists of a 3 μm x 0.75 μm titanium dioxide core on a silica bottom cladding. The 2D-PC structure surrounding the bend waveguide is composed of a triangular array of circular dielectric pillars having a height of 0.75 μm . The titanium dioxide waveguiding core layer is covered with PMMA in order to create a quasi-symmetric structure. A photonic band gap centered around 1.3 μm is obtained by a PC radius $r = 0.33a$ and lattice period $a = 0.450 \mu\text{m}$. The design of the whole structure is subsequently optimized by using a 3D Finite Difference Time Domain based computer code.

The ridge waveguide assisted by a 2D-PC has been fabricated by using electron beam lithography and reactive ion etching. For the pattern transfer we have used $\sim 50 \text{ nm}$ thin layer Cr metal etch mask obtained by means of a lift-off technique based on the use of bi-layer resist (PMMA/MMA).

The presence of the 2D-PC around the bend waveguide leads to a sharp increase of the transmission efficiency around 1.3 μm for curvature radius of 2.5 μm . The bend transmission results to be in the range between 0.76 and 0.85 when the thickness of the ridge WG and of the 2D-PC pillars is between 0.75 and 1.3 μm . This value is more than twice with respect to the bend waveguide without 2D-PC.

Keywords: Photonic Crystals, 90° bend waveguide, FDTD, Bilayer, EBL, RIE.

1. INTRODUCTION

Two-dimensional photonic crystal (2D-PC) structures have recently attracted a huge interest for their potential for the fabrication of ultracompact planar light-wave circuits. PCs are periodic dielectric media which can exhibit a photonic band gap (PBG), i. e. a range of forbidden frequencies and directions for the light propagation [1].

2D-PCs are very promising systems by virtue of their possibility to tailor the propagation of light [2-3] and to control the emission properties of light emitting devices [4-5] in a spectral domain ranging from the infrared to the ultra-violet with a high integration density. Most of the applications of 2D-PC are based on semiconductor materials such as silicon, GaAs/AlGaAs or InP. Titanium dioxide (TiO_2) is also attracting wide attention due to its large refractive index, to its transparency in the visible and in the infrared spectral range and to the possibility to be deposited by e-beam evaporation or sputtering on any substrate, thus enabling the fabrication of high density photonic circuits.

In order to achieve the miniaturization of photonic circuits, sharp bend waveguides with small curvature radius are required. In 2D-PC technology a sharp bend is normally obtained by introducing line defects in a two-dimensional photonic crystals slab structure [2-3].

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In this paper, we exploit the reflection property of 2D-Cs in order to improve the bend efficiency in a 90° bend ridge waveguide having bending radius of 2.5 μm and to reduce the size of planar light-wave circuits. We focused on the design and the fabrication of 90° bend ridge waveguides assisted by 2D-PCs, which act as efficient mirrors along the boundaries of the bend ridge thus reducing the in-plane losses. A 3D Finite Difference Time Domain (3D-FDTD) based computer code has been used in order to evaluate the transmission characteristics of the investigated bend waveguides. The devices design is optimized for quasi-TM polarization around 1.3 μm for the structure having bending radius of 2.5 μm . We focus on 1.3 μm , corresponding to the low-absorption window of fiber optic communication systems, due to its great interest as short haul communication wavelength.

By increasing the height of the core layer and of the dielectric pillars from 0.750 μm to 1.3 μm the bend efficiency of this 90° bend ridge waveguide is 0.85. The performance of both the 90° bend ridge waveguide and the same structure assisted by 2D-PC consisting of a triangular lattice of titanium dioxide (TiO_2) pillars covered with PMMA are compared. A detailed description of the nanotechnology processes necessary for the fabrication of 90° bend ridge waveguide assisted by a 2D-PC is shown. It includes the definition of the 90° bend ridge waveguide and the 2D-PC pattern by using electron beam lithography and an anisotropic CF_4 -based dry etch process. A thin layer Cr metal etch mask obtained by means of high quality lift-off technique, based on bi-layer resist (PMMA/MMA), is used for the pattern transfer. The resulting patterns have been morphologically characterized by scanning electron microscopy.

2. TITANIUM DIOXIDE 90° BEND RIDGE WAVEGUIDE ASSISTED BY 2D-PCs DESIGN

We have carefully designed a 90° bend ridge waveguide consisting of a TiO_2 ($n=2.177$) core on a silica (SiO_2 , $n=1.448$) bottom cladding having a bending radius of 2.5 μm . The TiO_2 waveguiding layer (thickness of 0.750 μm) grown by e-beam evaporation was sandwiched between a Polymethylmethacrylate (PMMA, $n=1.475$) upper cladding and a 10 μm thick SiO_2 bottom cladding. We covered the slab waveguide with PMMA, a transparent material whose refractive index value is similar to as SiO_2 , in order to maintain the symmetry of the structure. Figure 1 shows the cross section of the examined structure having a core thickness t_{core} of 0.75 μm and a core width w_{core} of 3 μm .

Fig. 1: Sketch of the basic structure.

The numerical analysis has been performed by means of a computer code based on 3D-FDTD method. FDTD approach is based on direct numerical solution of time-dependent Maxwell's equations and the update equations are obtained with the standard staggered grid and leap-frog time integration scheme [6].

The computational domain has been discretized by using cubic cells of $\Delta x = \Delta y = \Delta z = 50$ nm, while the time step has been assumed equal to $\Delta t = 6 \cdot 10^{-2}$ femtosecond. PML (Perfectly Matched layers) [6-7] absorbing boundary conditions have been used in order to truncate the computational domain, obtaining minimal values for reflections from the outer boundaries; PMLs are 20 cell thick in all directions and have a geometrical scaling for the conductivity profile indicated by the following expression :

$$\sigma_i(i) = -(\ln[R(0)] \ln(g / (2\eta \Delta i (g^{d/\Delta i} - 1)))) * (g^{1/\Delta i})^i \quad i=x,y,z. \quad [1]$$

$R(0)$ is the reflection error at the last cell of the PMLs, g is the scaling factor, Δi is the spatial discretization step for each direction $i=x,y,z$, η is the impedance of the medium and d is the thickness of the absorbing layer.

Initially a TM polarized time Gaussian pulse shaped wave centred at $\lambda = 1.32 \mu\text{m}$ is launched through the structures in order to determine the geometrical dimension for the waveguide that supports the fundamental mode; then, the fundamental mode has been used to excite the structure. Two time monitors (input section before the bend and output section after the bend) have been used to record the time evolution of each E and H field components. The field components have been transformed by FFT in order to compute Poynting vector components along the propagation axes. The bend efficiency has been obtained by the ratio between the transmitted power in the output waveguide and the incident power in the input waveguide.

Figure 2 (a) shows the bend efficiency versus wavelength for bending radius of $2.5 \mu\text{m}$. Around $1.3 \mu\text{m}$, the bend efficiency is about 0.33. This value is due to the low bending radius. The inset in figure 2 (b) shows the top view of the 90° bend ridge waveguide having bending radius of $2.5 \mu\text{m}$.

Figure 2 (b) shows the in-plane electric field E_y component time evolution along 90° bend ridge waveguide having bending radius of $2.5 \mu\text{m}$.

Fig. 2: (a) Bend efficiency versus wavelength for a bending radius of $2.5 \mu\text{m}$; (b) In-plane electric field E_y component time evolution.

We observe that a part of guided power is radiated out of the bend, due to the fact that this portion of power (tail of the mode) cannot travel sufficiently fast in order to stay in phase with the remainder of the guided mode. However, the tail is continually re-supplied with the power from the remainder of the guided mode, as it travels along the bend. The consequence of this fact is the diminishing of the overall amplitude of the guided mode, increasing the propagation distance.

A way to improve the bend efficiency and to reduce the in-plane losses in a 90° bend ridge waveguide is to increase the bending radius, which is the major limitation to the device density. In order to overcome this problem and to design compact photonic components, which can be packed in ultra-compact photonic circuits, we have introduced a 2D-PC structure along the boundaries of the bend ridge having bending radius of $2.5 \mu\text{m}$. The 2D-PC consisted of circular TiO_2 pillars in PMMA placed on a SiO_2 bottom cladding and having a finite thickness equal to $0.75 \mu\text{m}$.

The periodic arrangement of dielectric pillars creates a photonic band gap (PBG) for quasi-TM polarization around $1.3 \mu\text{m}$. Figure 3 shows the band diagram calculated by means of 3D Plane Wave Method (3D-PWM). The range of normalized frequency, in which light cannot propagate, extends from $\omega = a/\lambda = 0.3313$ to $\omega = 0.346$. In order to have a band gap centred around $1.3 \mu\text{m}$, the geometric parameters of the 2D-PC having height $h = 0.750 \mu\text{m}$ are $r = 0.150 \mu\text{m}$ and $a = 0.450 \mu\text{m}$, where r is the pillar radius and a the lattice constant.

Fig. 3: 3D band structure of the triangular lattice of TiO₂ pillars.

Based on these results, the designed 2D-PC mirror has been placed along the boundaries of the bend ridge in order to improve the transmission in the 90° bend waveguide. The light propagation properties have been then verified by means of 3D-FDTD simulations by using the same conditions described above.

Figure 4 (a) shows the top view of the 90° bend ridge waveguide surrounded by 2D-PC having a finite thickness equal to 0.75 μm (inset) and the bend efficiency versus wavelength for bending radius of 2.5 μm. Around 1.3 μm, the bend efficiency is about 0.76, which is almost twice with respect to the sample without 2D-PCs.

Fig. 4: (a) Bend efficiency versus wavelength for a bending radius of 2.5 μm; (b) In-plane electric field E_y component time evolution.

The energy flux of the mode propagating in proximity of the bend impinges on the pillars with different directions, which are not all included in the range of the band gap, therefore a non-perfect mirror action from photonic crystal is observed and the bend efficiency is limited. Moreover, some pillars of the photonic crystal have been removed in order

to allow the ridge to be curved in the periodic structure: the event is that the periodicity is not well kept along the bend, thus some point defects are introduced around the bend, affecting the transmission spectra. Figure 4 (b) shows the electric field E_y component time evolution in a 90° bend ridge waveguide with radius of curvature of 2.5 μm assisted by 2D-PCs. By comparing this in-plane electric field distribution with that of the conventional 90° bend ridge waveguide shown in Fig. 2 (a), the guided mode results to be more confined in the bend.

We also observed that the bend efficiency of this 90° bend ridge waveguide improves by increasing the height of the core layer and of the dielectric pillars. Figure 5 shows the bend efficiency versus wavelength of the 90° bend ridge waveguide surrounded by 2D-PC having a finite thickness equal to 1.3 μm . Around 1.3 μm , the bend efficiency is 0.85 and the guided mode is more confined in the bend, which is again twice than without 2DPC.

Fig. 5: Bend efficiency versus wavelength of the 90° bend ridge waveguide surrounded by 2D-PC having a finite thickness equal to 1.3 μm .

3. TITANIUM DIOXIDE 90° BEND RIDGE WAVEGUIDE ASSISTED BY 2D-PCs FABRICATION

We have evaporated 0.750 μm and 1.3 μm thick TiO_2 films on a SiO_2/Si substrate by e-beam evaporation. Subsequently the samples were covered with 0.140 μm two-layer positive resist PMMA/MMA, which has been used as electron beam lithography (EBL) resist for pattern definition and to obtain high quality lift-off. The resist films were deposited by the spin-coating technique and backed on a hotplate.

The 90° bend ridge waveguide with and without 2D-PC have been defined by EBL with an acceleration voltage of 2.5 keV and a beam current of 9.2 pA, carried out by a RAITH150 lithography system. A low value of energy exposure was used in order to decrease both the electron proximity effect caused by the scattering of electrons in the resist film and the charging effect due to the TiO_2 dielectric film. The pattern of the bi-layer resist exposed has been developed in a 1:3 mixture of methylsobutyketone/propanol (MIBK/IPA) at room temperature. Figure 6 shows scanning electron micrographs (SEM) of the 90° bend ridge waveguides after e-beam lithography. Figure 6 (a) shows the top-view of the 90° bend ridge waveguide and figure 6 (b) shows the top-view of the 90° bend ridge waveguide assisted by 2D-PCs which are magnified in figure 6 (c).

Fig. 6: SEM images of the fabricated structures: (a) Top-view of the 90° bend ridge waveguide. (b) Top-view of the 90° bend ridge waveguide surrounded by 2D-PCs. (c) Magnified top-view of the 2D-PCs pattern.

By means of a thermal evaporation, ~ 50 nm thin layer Cr metal etch mask has been obtained by means of a lift-off procedure based on the use of bi-layer resist, which consisted of the negative of the lithographic pattern. The Cr mask has been transferred down to the TiO_2 layer by reactive ion etching (RIE) through a CF_4 gas with a rf power set to 200 W and a CF_4 flow of 32 SCCM. The ridge depth was measured by AFM and resulted to be of $0.750\ \mu\text{m}$, stopped just before the SiO_2 cladding layer.

Figure 7 shows SEM images of the structure after lift-off and RIE. The 90° bend ridge waveguide and the TiO_2 pillars geometry are yet conserved and the 2D-PC WG device resulted successfully fabricated.

Fig. 7: SEM images after lift-off and RIE: (a) Magnified top-view of the 90° bend ridge waveguide. (b) Magnified top-view of the 2D-PCs pattern.

As final step before the optical characterization we covered the slab waveguide with PMMA in order to realize a quasi-symmetric structure. The input and output tapered shape of the bend ridge waveguide, as shown in figure 6 (a) and (b), allows to achieve an easy coupling between the optical fiber and the structure under measurement. An optical characterization of the fabricated structures is currently under study in order to verify the effect of the photonic crystals structures on the light transmission of 90° bend ridge waveguides.

4. CONCLUSIONS

In order to improve the transmission in the 90° bend waveguide having a bending radius equal to 2.5 μm and to reduce the in-plane losses, we have introduced a 2D-PC triangular lattice of dielectric pillars acting as efficient mirror along the boundaries of a bend ridge waveguide. The evaluated bend efficiency in the 90° bend ridge waveguide assisted by 2D-PC having finite height equal to 0.750 μm is about 0.76, greater than the value (0.33) obtained for the conventional 90° bend ridge waveguide. The 3D-FDTD analysis shows the effects of the finite height of the TiO_2 layer on the bend efficiency. In the 90° bend ridge waveguide assisted by a 2D-PC having finite height of 1.3 μm , the efficiency is as high as 0.85, more than twice with respect to a similar sample without a 2D-PC. A TiO_2 2D-PC pattern with the same parameters as in the simulation ($r = 0.150 \mu\text{m}$ and $a = 0.450 \mu\text{m}$) has been successfully fabricated by means of EBL, lift-off and RIE, which makes the 2D-PC technology a viable tool for the realization of sharp bend ridge TM waveguides.

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