Giant birefringence and tunable differential group delay in Bragg reflector based on tapered three-dimensional hollow waveguide

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A tunable Bragg reflector based on a tapered three-dimensional (3D) hollow waveguide (HWG) with variable taper angle has been proposed and demonstrated. A large grating coupling coefficient for a large reflection band and a giant birefringence of 0.01 have been achieved by optimizing the structure of the 3D HWG. The large birefringence causes a delay difference between the orthogonal polarizations and the variable taper angle provides tuning in the delay difference. A 13 ps tuning in differential group delay has been reported with a 3 mm long compact device, which can be used for adjustable compensation of polarization mode dispersion in optical fiber links. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3075058]

In long haul optical transmission systems, the degradation of transmitted optical signal from material and waveguide dispersions is a crucial problem. The dispersion, including polarization mode dispersion (PMD), is also a potential data rate limiting factor.[1] PMD occurs because of many intrinsic and extrinsic parameters including fiber core asymmetries, pressure, tension, vibration, and temperature fluctuations, which lead to different transmission speeds of orthogonal polarizations causing random pulse distortion and pulse broadening in data stream; PMD becomes severe at increased data rates over 40 Gbit/s and higher.[2] To avoid the degradation of signal in fiber optic links, PMD compensation is necessary. Large birefringence and tunable differential group delay (DGD) are needed to realize an adjustable PMD compensator, which can be achieved with a chirped Bragg grating filter to cancel the PMD in optical fibers.[3] A long fiber Bragg grating with some complicated tuning scheme is usually required to achieve large birefringence and wide tuning in DGD.[4] An on-chip control of DGD with the tuning scheme other than the thermal tuning can be useful to realize a compact, temperature insensitive, and low power consumption PMD compensator.

Tunable hollow waveguide (HWG) can be a potential candidate for widely tunable and temperature insensitive photonic integrated circuits,[5] where tuning can be realized by a variable air core using a microelectromechanical system actuator. The flexibility in designing the HWG makes it possible to build the photonic devices with a number of functionalities.[6,7] A number of tunable devices based on slab HWG have been proposed.[8,9] For compact and widely tunable photonic integrated circuits, a three-dimensional (3D) HWG can be realized by making a deep groove in an otherwise slab HWG.[10] The 3D optical confinement, with low propagation loss and low polarization dependence, in a tunable HWG can be achieved with a few hundred nanometer high step in one of the two multilayer mirrors.[11] Based on a tapered slab HWG, a planar Bragg reflector can provide chirping and an adaptable dispersion compensator can be realized.[12] In addition, air-core guiding in HWG gives us low temperature dependence.

In this paper, we show that a giant birefringence can be realized with a 3D HWG by optimizing the step height. A tapered 3D HWG-Bragg reflector has been proposed in which DGD has been tuned by varying the taper angle. The 3D HWG together with a tapered structure broadens the reflection bands of the Bragg reflector and a variation in the taper angle of top multilayer mirror varies the group delays of orthogonal polarizations. The effect of a variable taper angle on vertical polarization remains larger than that on lateral polarization, causing a difference in group delays of the two polarizations. A giant birefringence of 0.01 and a 13 ps tuning in DGD has been demonstrated experimentally even with a 3 mm long compact device. The low temperature dependence, an inherent property of HWGs, eases the complexity caused by temperature controllers.

The schematic side view of the tunable Bragg reflector based on a 3D HWG is shown in Fig. 1(a), in which a step

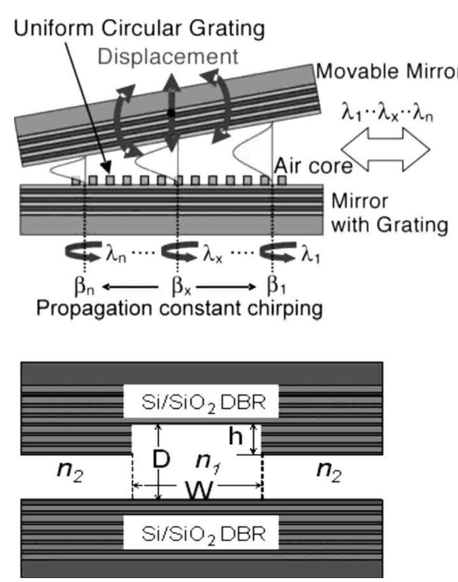

FIG. 1. (a) Side view of Bragg reflector based on tapered 3D HWG with variable taper angle and (b) basic cross section of steplike 3D HWG. All the layers in the top and bottom DBR mirrors are quarter wavelength thick. The effective index of the air core is n_1 and that of lateral air cladding is n_2, where $n_1 > n_2$ because of the difference in air gaps in the lateral direction.

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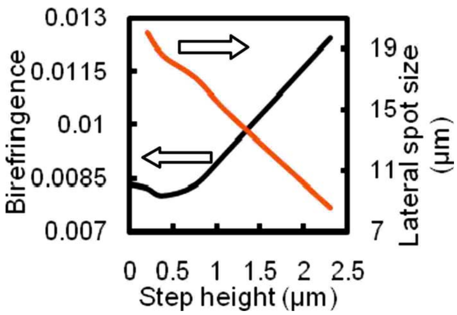

FIG. 2. (Color online) Computed effect of step height on birefringence and lateral spot size at an air core thickness of 5 μm. These results are for straight (without taper) 3D HWG.

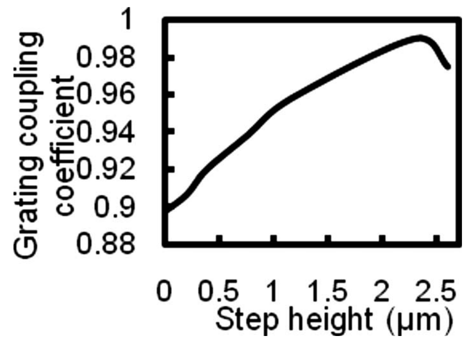

FIG. 3. Calculated grating coupling efficiency as a function of step height at a narrow air core thickness of 5 μm. These results are for straight (without taper) 3D HWG.

has been formed in a top multilayer mirror while a bottom multilayer mirror is loaded with a SiO_2 grating. The cross section of the basic 3D HWG is shown in Fig. 1(b); the air core thickness D is defined as shown. The quarter wavelength thick top and bottom multilayer mirrors provide strong optical confinement in the vertical direction. A step is formed in the bottom multilayer mirror with height h and width W. The effective index n_1 in the core region of the structure of Fig. 1(b) is larger than that of lateral cladding region (n_2) to confine light laterally.[10] The increase in step height leads to an increase in the lateral effective index contrast, which causes an increase in lateral confinement. The relation between lateral spot size and step aspect ratio (SAR) (defined by h/W) of 3D HWG, shown in Fig. 2, has been calculated using FIMMWAVE based on film-mode-matching method[13] with five pairs of Si/SiO_2 multilayer mirrors on top and with the same number in the bottom; the step height was increased by increasing the number of pairs in the lateral air cladding region of the bottom mirror. In the simulation, an operating wavelength of 1.55 μm was used. By increasing the SAR (increasing h), the lateral effective index contrast increases, which causes reduced lateral spot size. At a step height of 2.3 μm, the lateral spot size and propagation loss, respectively, are 8.5 μm and 1.2 dB/mm at a step width of 10 μm and air core thickness of 5 μm. The step width was fixed at 10 μm to roughly match it with the spot size of the standard single mode optical fiber for efficient coupling of the device with the fiber.

It is noted that this 2.3 μm high step strengthens the applicability of 3D HWG with an added feature of giant birefringence, shown in Fig. 2, where effect of step height has been studied on the birefringence, defined by $B=(\beta_{TE}-\beta_{TM})/\beta_{TE}$, where β is propagation constant. The birefringence increases with increasing step height because of the increase in lateral effective index contrast. The calculated birefringence at a step height of 2.3 μm is 0.0124 with a 5 μm thick air core. This giant birefringence, which is two orders of magnitude larger than that with other conventional fiber based technologies, can provide us compact devices with efficient functionality for PMD compensation among others.

For the fabrication of a tunable Bragg reflector based on 3D HWG, the top and bottom Si/SiO_2 multilayer mirrors have been prepared by electron beam evaporation. The 2.3 μm deep and 10 μm wide step is formed in a top multilayer mirror by dry etching followed by selective wet etching. The grating was fabricated on the bottom multilayer mirror by electron-beam lithography followed by dry etching at NTT Advanced Tech. Japan. The grating depth, pitch, and length are 500 nm, 860 nm, and 1 mm, respectively; the total device length is 3 mm. The larger step height discussed above carries multifold benefits of increased birefringence and reduced spot size because of an increase in lateral index contrast. Figure 3 shows the calculated grating coupling coefficient of the Bragg reflector versus step height. The grating coupling coefficient is defined as the overlap of the guided fundamental mode of the 3D HWG with the grating layer; it increases with increasing step height and after a certain value it begins to drop. At the step height around 2.3 μm or more, the fundamental mode of the 3D HWG is tightly confined in air and it begins to loose its overlap with the grating layer. The grating coupling coefficient is largest around 2.3 μm, which can enhance the reflection band of the Bragg reflector.

For the demonstration of high birefringence and tunable DGD, the taper angle of the top multilayer mirror can be precisely controlled with a high resolution stepping motor. The taper angle and the thickness of air gap can be precisely measured with a camera attached with the measurement setup.[6] For broadened reflected spectra and large dispersion, we introduce chirping by tapering one of the multilayer mirrors of 3D HWG. The measured reflected spectra of TE and TM modes at various taper angles are shown respectively in Figs. 4(a) and 4(b), where an overlap between the reflection bands of TE and TM modes has been observed. The taper angle has been varied from −0.038° to 0.057°. The taper angle 0° refers to the straight 3D HWG (without taper). Increasing the taper angle has the effect on reflection bandwidths of TE and TM modes; the bandwidth increases by increasing the taper angle, because of the increased spatial chirping in the Bragg wavelength. The net insertion loss remains less than 2.5 dB for a 3 mm long device.

In HWGs, because of air core guiding, the angle of incidence of the fundamental mode is smaller than Brewster's angle, which makes the orthogonal polarizations out of phase causing large polarization dependence. Also, the presence of a step in one of the multilayer mirrors affects the orthogonal polarizations and polarization dependence can be further increased by varying the step height. As shown in Fig. 2, by increasing the step height, birefringence can be increased; an ultrahigh birefringence of 0.012, much larger than that of the slab HWG (step height $h=0$), can be achieved in a straight 3D HWG with a 2.3 μm high and 10 μm wide step at a 5 μm thick air core. The measured birefringence of the 3D HWG Bragg reflector as a function of taper angle is shown in

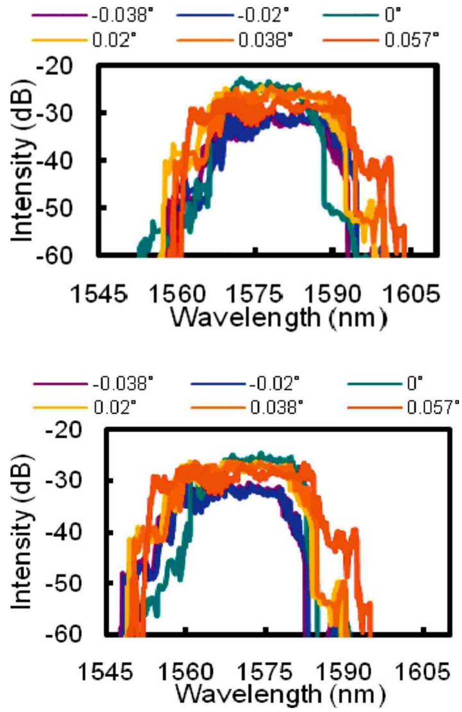

FIG. 4. (Color online) Measured reflected spectra of tapered Bragg reflector at different taper angles (a) for TE-mode and (b) for TM-mode.

Fig. 5(a), where birefringence is defined by $B=(\lambda_{TE}-\lambda_{TM})/\lambda_{TE}$, where λ is the center Bragg wavelength. A small variation in birefringence has been observed by varying the taper angle. The birefringence is less dependent on the taper angle; the birefringence remains around 0.01, which is in agreement with Fig. 2, and is almost two orders of magnitude larger than the birefringence of fiber Bragg gratings.[3]

The dispersion and hence the group delay in HWGs can be enhanced by introducing a taper.[12] The large birefringence causes a delay between TE and TM modes of the 3D HWG and the variable taper angle can enhance the group delays and delay difference between these two orthogonal polarizations. The measured group delays of TE and TM modes of the Bragg reflector based on tapered 3D HWG at various taper-angles are shown in Fig. 5(b). By increasing the taper angle, group delay for both polarizations increases because of the enhancement of chirping in the propagation constant of the guided mode.[12] The increasing taper angle has larger effect on TE (vertical) polarization than that on TM (lateral) polarization, as the taper-angle variation, being a vertical movement, affects the vertical polarization to a little more extent, as shown in Fig. 5(b). Thus at larger taper angles, the difference between group delays of TE and TM modes becomes larger, which causes a tuning in DGD, where DGD is defined as the difference of group delays between TE and TM modes. Figure 5(b) also shows tuning in DGD as a function of taper angle. By increasing the taper angle from −0.038° to 0.057°, DGD increases from 1.5 to 14.6 ps, providing us a 13.1 ps tuning in DGD, with a 3 mm long compact device. The large birefringence and tunable DGD of the proposed compact 3D HWG Bragg reflector makes it a good candidate for dynamic adjustable compensation of PMD in high bit rate and high speed transmission in optical fiber links. The giant birefringence can be used in tunable polarization manipulating devices based on a tunable 3D HWG.

In conclusion, the birefringence of a 3D HWG can be controlled with the step-height variations. A giant birefringence of 0.01 has been experimentally achieved with a 3 mm long compact Bragg reflector based on a tapered 3D HWG. A 13 ps tuning in DGD has been demonstrated by varying the taper angle. These results show the possibility of a compact, temperature-insensitive, and adjustable PMD compensator based on a tapered 3D HWG Bragg reflector for high bit rate and high speed fiber optic links.

Also, the large birefringence of 3D HWGs with a variable air core can be used in designing the tunable polarization manipulating devices. The propagation characteristics of steplike 3D HWG can be tailored to realize a number of temperature-insensitive and tunable photonic devices for a variety of applications.

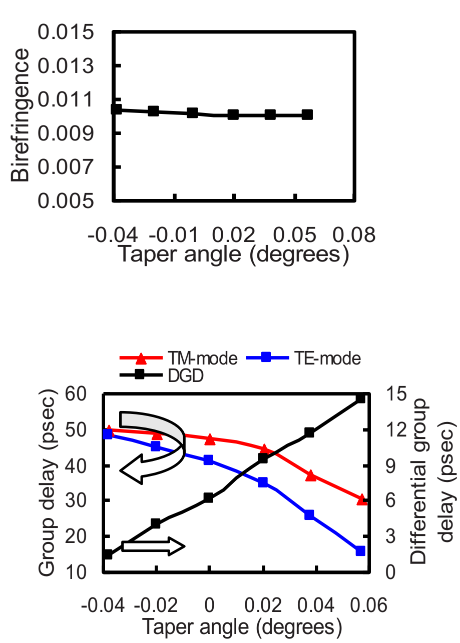

FIG. 5. (Color online) (a) Measured birefringence vs taper angle, (b) measured group delays of TE and TM modes, and DGD as a function of taper angle.

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