Review Article

Multilayer Optical Waveguides As Isolators, Polarizers And Other Optical Devices : A Review

Abstract

An optical waveguide is a structure guiding the wave of light, limiting it to travel through the given and specific path. If the size of transverse dimensions is bigger than the guided light wavelength, then total internal reflection (TIR) and geometrical optics can be used to explain the working principle of geometrical optics. There is a strong control from Photonic Band Gap (PBG) structures over light and some of the best use cases of such structures rely on the functionalities while using defects in lattice which had led to the Photonic Crystal (PhC) heterostructure design. The photonic band structure is influenced by the defects in the PhC and it can cause the confinement or flow of light apart from specific pathways in the property and crystal of those structures.

In this paper, we investigate the application areas of polarizers, isolators and other optical devices in optical waveguides. The loss occurred in the added layer and changes in the properties of the waveguide is also discussed. It is also observed that resonant layer effect (RLE) can improve and play a pivotal role to develop a lot of devices like polarizers, modulators, and isolators.

Keywords – optical waveguide, polarizers, modulators, isolators, total internal reflection, resonant layer effect, RLE

Introduction

Chip-level circulators and isolators are important for operating several photonic IC chips and it is challenging to implement those components on silicon with the process that supports foundry combining bandwidth and high insulation ratio with physical footprint and low insertion loss. In order to deal with this issue, several strategies are explored with “magneto-optic (MO) ring resonators” (Bi et al., 2011; Kono et al, 2007; Pintus et al, 2011; Tien et al., 2011)[1-4], completely dynamic reciprocity (Shi et al., 2015)[5], and “Mach-Zehnder interferometers” (Shoji et al., 2008; Du et al., 2018; Zhang et al., 2019l; Yan et al, 2020)[6-9], which are some of the most successful strategies till date. Considering the operation of such devices, the “nonreciprocal phase shift (NRPS)” is not so strong perturbation (with a small change in constant of propagation “$\Delta\beta/\beta \sim 10-4$” between back and forward modes), imposing some fundamental tradeoffs between bandwidth, isolation ratio, compactness, and insertion loss (Shoji et al., 2016)[10].

Also called as “Photonic Band Gap (PBG),” the photonic crystals (PhCs) are periodic and artificially designed structures where stop bands rise up with refractive index modulation for electromagnetic signals in a specific range (Villeneuve & Piche, 1992a; Villeneuve & Piché, 1992b; Qiu & He, 1999; Qiu, 2002)[11-14]. Hence, these structures are helpful to route, confine, localize, suppress, disperse, split, and filter electromagnetic signals. PBG structures have a lot of novel applications and gained a lot of attention over the years. The optical properties like anisotropy, high dispersion, and light localization of photonic crystals rely on the structural parameters like period of modulation, refractive index, lattice modulation, and modulation period.

Simply speaking, photonic crystal properties can be controlled by making changes to design parameters and attaining complete freedom in optical devices which are specific to design application. The polarization sensitivity in these structures can be used to design several devices which are sensitive to polarization, like polarizers, lasers, polarization splitters etc (Nagpal & Sinha, 2004; Bayindir & Ozbay, 2002; Kamp et al., 2004; Camargo et al., 2004; Rinnerbauer et al., 2004; Niemi et al., 2005; Wu et al., 2004; Ohtera, 1999)[15-22]. These are some of the properties that make photonic crystal structures stand out.

The layer of “High Refractive Index” features a second insight of the basic mode within or above the optical waveguide clad. The loss in the added layer can overcome the overall loss of waveguide in the added layer and it can selectively suppress the guided modes. This effect may improve the operation of several devices of optical waveguides. In combination with secondary guided modes, the secondary field peak may appear and it can be sensitive to the refractive loss, location, thickness, and wavelength of added layer and operation. The “Resonant Layer Effect (RLE)” is the phenomenon of this process.

A lot of optical waveguide devices like polarizers, isolators, grating-feedback reflectors, modulators, and other optical devices can be improved or made by RLE. The RLE may generally appear and cause high modal loss. The RLE is receptive towards the physical waveguide. Hence, even minimal changes in the properties of waveguide can cause huge changes in loss. It is easy to integrate this concept of RLE into any optical waveguide. The RLE is much like the resonance effect in the lasers of “channeled substrate planer (CSP)” which suddenly had uneven Al composition (Evans et al., 1987)[23].

There are several useful devices depending upon modal loss variations. Resulting from the loss, the isolators vary with the direction of propagation. While responding to magnetic or electric fields or any physical input, there is a change in loss from isolators. Diffraction grating can be possible due to the periodic change in loss. Polarization makes changes in polarizers. For example, a strong RLE may show up with a transverse electric (TE) mode and, hence, it can have a wide secondary resonant layer (RL) peak, while there is no secondary peak with a transverse magnetic (TM) mode of that structure (Hammer et al., 2004)[24]. In this article, we are going to discuss multilayer optical waveguides in the form of polarizers, isolators, and other optical devices.

Discussion

1. Optical Isolators and Polarizers on Rectangular Waveguide

When making single-path waveguides, a chirality-backed approach can be viable as polarizer or optical isolator is mentioned. Slanted rectangular grooves introduced the chirality on waveguide walls and the waveguide is rectangular. Chirality of the waveguide is manifested as a robust curved dichroism and is ideal to transmit one light polarization and reflect another. It is possible to achieve optical isolation when it comes to propagating circular polarization with the placement of a chiral waveguide ahead of a non-chiral device. Significant dichroism is exhibited by even the crudest of chirality (Shvets, 2006)[25].

It is well known that total integration of photonics and electronics should be achieved on a submicron scale in a few years to come (Kobrinsky et al., 2004)[26]. Hence, the integrated photonic toolbox is presenting the recent advances and expanding in photonic crystals **(**Vlasov et al., 2005)[27], magneto-optic materials, and dielectric waveguides (Vlasov & McNab, 2004)[28]. Optical polarizers (devices transmitting one light polarization only) are especially challenging to be made in the form of integration and isolators are relevant (there are 1-path optical aspects suppressing reflection of one polarization to the minimum).

Rectangular waveguide is used to solve the issues of making one-way linear and optical elements with a chiral perturbation (that are set as individual right-sided helix) to its side walls. Due to individual cross sections of the waveguide and crude chirality implementation with timely set grooves in the waveguide wall, it is quite easy for the device to be integrated and fabricated with other ranges of optical waveguides. Propagation of laser fields which are circularly left and right circularly polarized may vary significantly. There is an existence of a frequency band for which the propagation of only LHCP waves effectively makes an easy circular polarizer using chiral waveguide (ChW) (Wang et al., 2005)[29].

With the right "double-helical perturbation", the twisted chiral fiber gratings have been recommended for the refractive index as selective polarization filters in microwave (Kopp & Geneck, 2003)[30] and optical range (Kopp et al., 2004)[31] of frequencies. Twisting cannot be made possible with silicon waveguides, which are not easy to fabricate with varied cross-section from rectangular cross-section. The helicity of the proposed structure has highly crude and hidden turn and step symmetry (which is neither helix nor perfect). Hence, they can be implemented well in integrated optics. The individual geometry of grooves ensures further suppression and simplification of structure and Bragg scattering (Shvets, 2006)[25].

2. Plasmonic Waveguide Polarizer with elevated extinction ratio

Malekzadeh et al (2020) [32] developed a unique approach to elevate the extinction ratio of "plasmonic waveguide polarizer". They covered aluminum in multi-strips 20 microns pattern atop the SU-8 waveguide to stimulate the plasmons of the surface. The extinction ratio of this polarizer is presented in the experimental and simulation output and it is found to be above the single-strip polarizers with the same length of aluminum coating because of loss of coupling between uncoated and AI-coated areas along with scattering at the metal's edge. This polarizer had around 46 dB of extinction ratio at 1550 nm of wavelength and 26.8 dB of ratio at 980 nm.

The integrated photonic circuits have been designed to turn the free-space and heavy setup into a nano- or micro-sized chip. In optical setup, each aspect must have a miniaturized integrated chip performing the same function. Polarizer is widely used in several optical devices and plays a vital role in optical elements. It is widely applicable in modulators, optical switches, optical gyroscopes, sensors, and quantum optics. Hence, it is very vital for optical setups and it is very important to fabricate the same in integrated aspects.

3. Magneto-Optic Isolators

Grede et al. (2021)[33] have found significant improvement in the trade-off between insertion loss and isolation bandwidth using coupled magneto-optic ring isolators around the exceptional point (EP). Isolation bandwidth relies on the square root of NRPS or “non-reciprocal phase shift” by using combined ring isolators at exceptional points in EP sensors. It improves the bandwidth with small NRPS rather than common linear dependence. There is around 50% rise in 3 dB insertion loss and 20 dB isolation bandwidth in practical interest for a specific pair of rings. There is a great advantage of EP operation in its growth in the range of material resonances of magneto-optic isolators and they are likely to extend to different on-chip isolators relying on feeble non-reciprocal perturbations.

On-chip circulators and optical isolators are important for managing various photonic IC chips while implementing those parts on silicon with the process that is compatible with foundry combining low insertion loss and high isolation bandwidth and ratio with challenging physical footprint. This problem has been fixed with several strategies (Shoji et al., 2015; Lira et al., 2012; Kittlaus et al., 2021)[34-36] . But “Magneto Optic Ring Resonators" (Bi et al., 2011; Kono et al., 2007; Pintus et al., 2011)[1-3], fully dynamic reciprocity (Shi et al., 2015)[5] and “Mach-Zender interferometers” (Du et al., 2018)[7] are some of the most effective strategies till date.

Underlying these devices’ operation, the “nonreciprocal phase shift (NRPS)” is a destabilized perturbation (with a small change in constant propagation, back- and forward-going modes at “Δ□/□∼10−4Δβ/β∼10−4”), imposing small exchanges between bandwidth, isolation ratio, compactness and insertion loss (Shoji et al., 2016)[10]. It is concluded that ring isolators at exceptional points lead to reliance of isolation bandwidth on NRPS sublinearly while improving the performance that is possible to achieve from the weedy magnetic-optic response of existing materials. It is possible to recast the essence of this result in common language just by claiming that using the NRPS is more effective for splitting the combined ring resonance as compared to shifting one.

The isolator performance can be improved with other feeble “non-reciprocal perturbations” (Lira et al., 2012; Kittlaus et al., 2021)[35-36] that could also make the most of well-designed exceptional points. The NRPS will be placed in the bottom ring and active systems will have the top ring apart from passive isolators and the bigger opportunity is in overarching need to integrate isolators and lasers in the photonic IC applications.

4. Photonic Band Gap for Optical Waveguide Polarizer

Sinha and Kalra (2006) [37] proposed a new optical waveguide polarizer design which depends upon photonic band gap. They have applied a numeric method on the basis of a limited difference time method to design and analyze the polarizer based on the photonic band gap. They have tested the performance with transmittance and degree of polarization. They designed the defect modes to achieve the polarizer action in the structures of photonic band gaps.

Photonic Band Gap (PBG) or “Photonic Crystals (PhCs)” are periodic and artificially designed structures where bands are stopped with the rise of refractive index modulation for certain frequency of electromagnetic waves (Villeneuve & Piche, 1992; Qiu & He; 1999; Qiu, 2002)[12-14]. Hence, it is possible to use these structures to route, confine, localize, suppress, disperse, split, and filter those waves. Photonic band gap structures have been widely used over the years for several novel applications. Photonic crystals have a lot of optical properties like high dispersion, light localization, and anisotropy as per the parameters like period of modulation, depth of refractive index modulation, and its lattice type.

Simply speaking, it is not possible to control PhC properties by making changes to design parameters. Hence, the researchers have great freedom to design optical devices that are specific to the application. The polarization sensitivity in such structures is one of the best parts of PhC structures that can design several devices that are sensitive to polarization like polarizers, lasers, and polarization splitters, etc. (Nagpal & Sinha, 2004 [15]; Kamp et al., 2004[17]; Camargo et al., 2004[18]; Niemi et al., 2005)[20]. The researchers have capitalized the PhC polarization sensitivity and absolute photonic band gaps to design photonic crystal polarizers. Optics have polarizers to transmit one polarization state and block either part of polarization with the properties of reflection, absorption, and refraction. Pseudo band gaps have been reported earlier in PhCs.

5. Resonant Layer Effect Polarizers

Hammer et al. (2004)[24] tests the effect of the layer effect of high-refractive index over the clad optical waveguide. A resonance is reflected in the confinement layer of fundamental mode in an added layer with ideal design. This resonance relies on the thickness, location, wavelength, and complex index of operation of the added layer. Major changes in loss are reflected with small variations in properties of waveguide if this added layer consists of loss. The researchers described this phenomenon as “Resonant-Layer Effect or RLE”. A lot of devices, such as polarizers, isolators, and modulators can be improvised and/or developed with RLE.

The integratable in these illustrations gives the isolation of 240-dB/cm and insertion loss of 13 dB/cm, around 0.8-dB/cm of insertion loss is recorded with 90-dB/cm of integratable polarizer, and electric fields of 5Vm are required in 300m modulator for modulation of 45% of intensity. The integration with several material systems is allowed by the resonant layer with the waveguide.

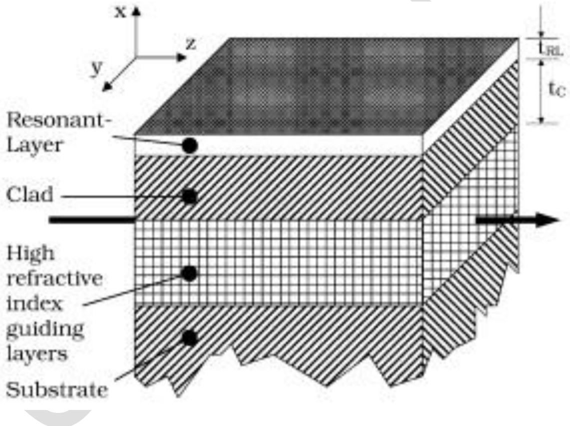

Fig. 1 – RLE Optical Waveguide Schematic Diagram (Hammer et al., 2004)[24]

Considering the above structure of optical waveguide (Fig. 1), a loss-based high-index layer has been applied atop the clad waveguide having doped and undoped quartz layers (like optical fiber layers). The RLE will lead to broadband wavelength filter and polarizer in this illustration. The Resonant Layer is the “perfluorocyclobutyl polymer plastic” or any other kind of polymer (Ballato et al. 2003)[38], which consists of a dye with decent 1.55m absorption of wavelength and it is positioned as resonant layer of waveguide.

6. Isolators Using The Resonant Layer Effect

If the resonant layer is formed with ferromagnetic material, it is possible to obtain an isolator. With low forward insertion loss and ideal isolation, it is easy to produce the isolators with the presence of resonant layer effect. The RLE is absent when the same arrangement works as an isolator but it results in inferior performance with higher forward loss of insertion (Zaets & Ando, 1999)[39]. The resonant layer of “Ferromagnetic Semiconductor Composite (FSC)” may have distributed ferromagnetic particle size in nanometers across the semiconductor host.

The ion implantation or epitaxial growth (Shimizu & Tanaka, 2002)[40] may have generated the composites along with annealing (Budai et al., 1997)[41]. It is possible to use those FSC layers with optic materials and semiconductor waveguides. Instead of constant ferromagnetic layer having the weight similar to that of ferromagnetic material, a composite reduces the optical loss which has ferromagnetic particles of nanometer size in FSC layer, while the magneto-optic Kerr effects and Faraday rotation are similar (Baba et al., 1996; Baba et al., 1997)[42-43].

7. Modulators Using The Resonant Layer Effect

The $LiNbO_3$ strips separate a Ti-$LiNbO_3$-strip guide of W_F width off two Ti-$LiNbO_3$ strips of W_{RL} width doped for having loss. In this symmetric range, the lossy and doped strips alternate for planar guides RLs. At the values of W_C, W_F and W_{RL} and other indexes, other guided intensity peaks are covered under the regions of lossy strips. The loss strips are amplified by the secondary peaks. There are high resonance losses with large secondary peaks and small modal losses with off-resonance on small secondary peaks. The refractive indexes can be changed by applying voltage around the electrodes on the strip guide. The on-resonance distribution of the field can be changed with vast secondary peaks to the distribution above the resonance with minimal or small secondary peaks (Hammer et al., 2004)[24].

The field distributions of the device are estimated with the right index method by resolving the 5-μm thick Ti-$LiNbO_3$ layer with lowest order TE planer modes and without $LiNbO_3$ substance losses. The estimated and actual parts of propagation are consistent in both the cases and are offering proper modal loss and refractive index. The TM mode propagation constant of the planer guide with W_{RL}, W_C and W_F thickness layers and loss and refractive index of effective values are calculated for estimating modulator efficacy (Hammer et al, 2004)[24].

Conclusion

The performance of isolators, polarizers, modulators, and other devices of optical waveguide can be improved with high-refractive index having the right amount of loss and thickness to the cladding layer. It is worth noting that the waveguide loss is highly dependent on small variations in properties of the waveguide due to the peak of the secondary field in the added resonant layer effect at the right thickness. It is also possible that isolation can be improved with RLE and so is the insertion loss in isolators. This effect is known to control the insertion loss and improve polarization ratio in polarizers, while cutting down the length of electro-optic modulators and raising the out-coupling and feedback of gratings.

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