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Design of PLC Triplexer Using Three Waveguide Interferometer

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A novel planar lightwave circuit (PLC) triplexer using a three-waveguide interferometer (TWI) is proposed and examined using the transfer matrix and the beam propagation methods. The proposed triplexer consists of two three-waveguide couplers and three waveguides connecting the couplers. Simulation for the TWI triplexer shows the excess losses of 0.03 dB and 0.94 dB with the crosstalks of -22.3 dB and -14.5 dB in reception, respectively, for the wavelength of 1490- and 1550-nm, while showing the excess loss of 1.75 dB in transmission for the wavelength of 1310 nm. The proposed design shows compact feature as short as 11.5 mm for the refractive-index contrast of 0.45%.

Keywords : Three-waveguide interferometer, Mach Zehnder interferometer (MZI), optical filter, planar lightwave circuit (PLC), planar waveguides, triplexer.

OCIS codes : (230.7390) Waveguides, planar ; (230.3120) Integrated optics devices ; (230.7380) Waveguides, channeled

I. INTRODUCTION

Triplexer is one of the key components in a fiber-to-the-home (FTTH) passive optical network system. Conventional types of triplexers are assembled with discrete components (i.e. laser diode, photodiode and thin film filter). Recently, several studies have been made on planar lightwave circuit (PLC) triplexers [1-5], since the PLC is perceived to be the most promising technology for mass production at low cost for FTTH application.

PLC triplexers which accommodate wavelength-division multiplexer (WDM) filters in the grooves of waveguide gaps are proposed [1,6]. However, they require a painstaking process like embedding of thin film filter in the gap, and therefore may suffer from relatively high cost and limited yield in manufacturing.

For this reason, a PLC triplexer of all-waveguide type using Mach-Zehnder Interferometers (MZIs) was proposed [2]. The MZI is basically a two-port device in input and output,. Therefore, more than two MZIs must be cascaded to separate signals in three-wavelength bands: the first MZI separates the 1310 nm wavelength from the 1490-1550 nm band, and the second MZI separates the 1490 nm from the 1550 nm wavelength. Such cascading of more than two stages of MZI increases the chip size and the production costs.

In this work, we propose a three-waveguide interferometer (TWI) which can separate bi-directionally the 1310 nm and the 1490/1550 nm channels of wavelengths at a single stage, and we discuss its performances as a triplexer.

II. DESIGN

The proposed three-waveguide interferometer consists of two three-waveguide couplers and three waveguides connecting the couplers as shown in Fig. 1. In this work, we assume that the core and cladding of the wave-

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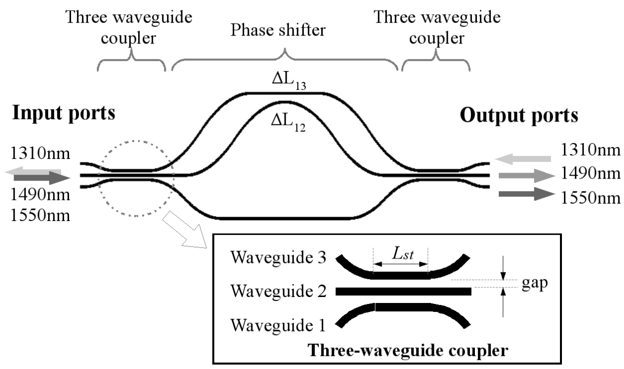

FIG. 1. Schematic structure of proposed three-waveguide interferometer triplexer.

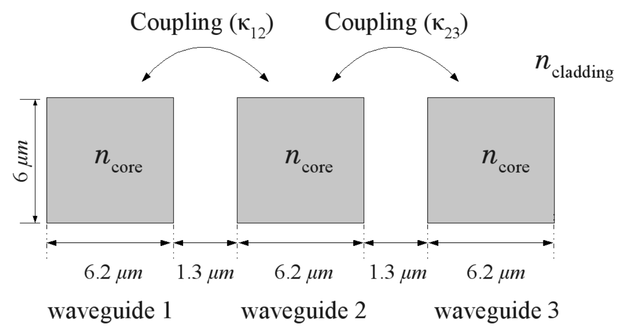

FIG. 2. Cross-sectional view of the three-waveguide coupler.

guides are both silica-based materials. The refractive index of the cladding is 1.4446 and the index contrast between the core and the cladding is 0.45%, which is commonly used in silica-based PLC devices for good coupling to optical fiber. The cross-sectional structures of the waveguides are buried square, and the width and height of the core is 6.2 μm and 6.0 μm, respectively, for single mode operation in the wavelength range of 1310-1550 nm.

The three-waveguide coupler consists of three waveguides which have the same cross-sectional cores as shown in Fig. 2. The gaps between the neighboring cores are all the same at 1.5 μm commonly realizable in the conventional process of fabrication and the gap provides strong coupling between the neighboring waveguides to minimize the length of the coupler. We assumed that the direct coupling between the waveguide 1 and 3 is negligible since the distance between waveguide 1 and 3 is sufficiently large. The coupled-mode equations of the three waveguide coupler are given by

$$\begin{aligned} \frac{d}{dz}A(z) &= -j\kappa_{12}B(z)\exp(-j(\beta_2-\beta_1)z) \\ \frac{d}{dz}B(z) &= -j\kappa_{21}A(z)\exp(-j(\beta_1-\beta_2)z) \\ &\quad - j\kappa_{23}C(z)\exp(-j(\beta_3-\beta_2)z) \\ \frac{d}{dz}C(z) &= -j\kappa_{32}B(z)\exp(-j(\beta_2-\beta_3)z) \end{aligned} \tag{1}$$

Where, A(z), B(z), and C(z) are the amplitudes of the optical mode-fields in the waveguide 1, 2, and 3, respectively. κ_{ij} and β_i are the coupling coefficient between waveguide i and j and the propagation constant of the waveguide i, respectively.

Since all three waveguides in this work have the same cross-sectional dimension, the coupling coefficients and propagation constants can be expressed by

$$\begin{aligned} &\kappa = \kappa_{ij} = \kappa_{ji}, &&(i, j = 1,2,3) \\ &\beta = \beta_k, &&(k = 1,2,3) \end{aligned} \tag{2}$$

By solving (1), the transfer matrix of the three-waveguide coupler is obtained.

$$M_{cpl} = \begin{pmatrix} \beta+\frac{1}{2} & \alpha & \beta-\frac{1}{2} \\ \alpha & 2\beta & \alpha \\ \beta-\frac{1}{2} & \alpha & \beta+\frac{1}{2} \end{pmatrix} \tag{3}$$

where,

$$\alpha = -\frac{j}{\sqrt{2}}\sin(\sqrt{2}\kappa L_{cpl}), \quad \beta = \frac{1}{2}\cos(\sqrt{2}\kappa L_{cpl}),$$

and L_{cpl} denotes the length of the coupler.

The three-waveguide phase shifter connecting the two three-waveguide couplers consists of three waveguides of which the path lengths are different from each other as shown in Fig. 1. The transfer matrix of the three-waveguide phase shifter is expressed by

$$M_{ps} = \begin{pmatrix} \exp(jk_0N\Delta L_{13}) & 0 & 0 \\ 0 & \exp(jk_0N\Delta L_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{4}$$

where, N, k_0, and ΔL_{ij} are the mode index of the waveguide, the wave-number in vacuum, and the path-length difference between waveguide i and j, respectively.

The transfer matrix of TWI, which consists of a three-waveguide phase shifter embedded between two identical three-waveguide couplers, is straightforwardly given by

$$[\mathrm{M}_{TWI}] = [\mathrm{M}_{cpl}]\cdot[\mathrm{M}_{ps}]\cdot[\mathrm{M}_{cpl}] \tag{5}$$

If the optical signal is fed into the center waveguide of the TWI, the input matrix can be written by $\mathrm{M}_{in} = (0, 1, 0)^{\mathrm{T}}$. Then, the output matrix is given by

$$[\mathrm{M}_{out}] = \begin{pmatrix} A_{out} \\ B_{out} \\ C_{out} \end{pmatrix} = [\mathrm{M}_{TWI}]\cdot[\mathrm{M}_{in}] \tag{6}$$

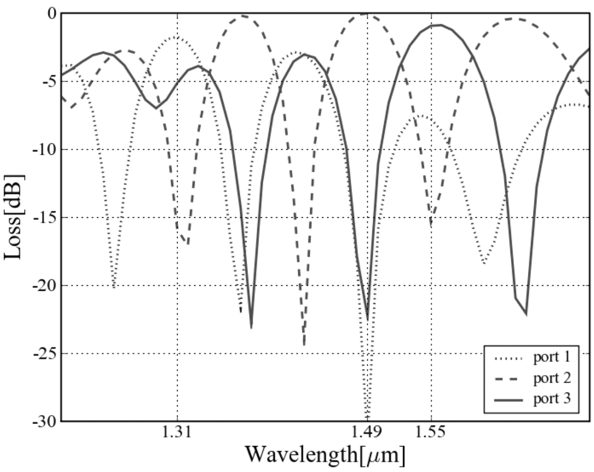

FIG. 3. Simulation results for wavelength characteristics from three output ports of the TWI triplexer. TM mode, waveguide width is 6.2 μm, ΔL_{12} is 10.77 μm, ΔL_{13} is 12.33 μm, and L_{cpl} is 1420 μm.

and the optical powers at the output ports are given by $(A_{out}A_{out}^*, B_{out}B_{out}^*, C_{out}C_{out}^*)$.

For operation as a triplexer, the TWI should separate and feed the 1310-, 1490-, and 1550-nm wavelength efficiently into the proper channels of waveguide 1, 2, and 3, respectively. We numerically calculated the equation (6) and searched for the optimized spectral characteristics varying parameters such as L_{cpl}, ΔL_{12}, and ΔL_{13} in the transfer matrix (6). In this work, the optimized L_{cpl}, ΔL_{12}, and ΔL_{13} are found to be 1420 μm, 10.77 μm, and 12.33 μm, respectively.

Since the coupling between two neighboring waveguides occurs not only in the straight segments (L_{st}), but also in the bent segment of the coupler (L_{bend}), we analyzed numerically the three-waveguide coupler using a three-dimensional beam propagation method (BPM), and modified the coupling length L_{cpl} to be the sum of L_{st} and L_{bend}. The bending radius of the waveguides is 10000 μm in this work. The modified length of the straight segment of the coupler L_{st} obtained by the BPM simulation is determined to be 935 μm.

The transmission characteristics of the optimized TWI triplexer are shown in Fig. 3. The insertion loss for the 1310 nm upstream port is shown to be 1.78 dB and is denoted by the dotted line. The insertion losses for the 1490 nm and 1550 nm downstream ports are shown to be 0.03 dB and 0.88 dB, and are denoted by the dashed lines and solid lines respectively. We can expect that additional losses like fiber coupling loss are negligible. The waveguides in this work have 0.45% index difference with buried channel type, and the coupling loss to common single-mode fiber is less than 0.1 dB.

In common applications of triplexers, optical transmitter modules require an optical power of 0 dBm.

TABLE 1. TE and TM characteristics of the TWI. W is waveguide width and the height is fixed to be 6.2

Insertion Loss [dB]

	TE			TM		
	W=6.0	W=6.2	W=6.4	W=6.0	W=6.2	W=6.4
Port 1 (1310 nm)	1.79	1.78	2.42	1.84	1.75	2.33
Port 2 (1490 nm)	0.03	0.03	0.04	0.03	0.03	0.04
Port 3 (1550 nm)	1.27	0.88	0.95	1.45	0.94	0.86

Channel Crosstalks of downstream ports [dB]

	TE			TM		
	W=6.0	W=6.2	W=6.4	W=6.0	W=6.2	W=6.4
Port 2 (1490 nm)	-23.92	-21.94	-20.66	-24.46	-22.27	-20.83
Port 3 (1550 nm)	-19.01	-13.02	-8.04	-20.94	-14.45	-9.13

There is some penalty in the optical power for upstream 1310 nm wavelength in this design. However, we expect that the coupling of LD to planar optical waveguide can be improved further compared to the typical coupling efficiency of 40% in the current TOCAN package of LD to an optical fiber, then compensate the loss of 1310 nm wavelength channel in this design. Instead, we placed more emphasis on the low loss of downstream port rather than that of the upstream port.

In the actual silica-based PLC fabrication process, the width of waveguide core becomes slightly different from the desired value, e.g., 6.2 ± 0.2 μm. The waveguide -width and polarization dependence upon the waveguide width error is investigated using transfer matrix method and the results are shown in Table 1. The results show that the insertion losses of the downstream channels will be maintained to be less than 1 dB when the waveguide width is in the range between 6.2 and 6.4 μm.

In conventional triplexer specifications, the 1310 nm band has a wide range, e.g., 1310 ± 50 nm in EPON. In the proposed TWI design, the 3 dB bandwidth of the upstream channel is about ± 30 nm. Although this bandwidth is narrower than that of the commercial triplexer specification, the proposed triplexer using appropriate laser diodes such as DFB-LD's with wavelength range of 1310 ± 10 nm or narrower can be acceptable.

The crosstalks between the downstream ports are less than about -22 dB for the 1490 nm port and about -13 dB for the 1550 nm port. One may consider that an additional stage of the MZIs might be cascaded, in the same way as shown in [2], to each output ports of the TWI-triplexer in order to improve the crosstalk characteristics.

The total size of the TWI triplexer in this work shows a compact feature of only 11.5 mm × 0.35 mm, although the index contrast of the TWI waveguide is chosen to be as low as 0.45%. A PLC triplexer of conventionally cascaded MZI with the same index contrast of 0.45% would be more than two times larger than that of the

TWI triplexer, because it uses MZIs with only two input and output ports while a triplexer uses three wavelengths. Even though an additional stage of MZIs is cascaded for improving the crosstalk-performances, it is expected that the total size of the device will be much smaller than that of the triplexer consisting of MZIs only.

III. CONCLUSION

In this work, a novel PLC triplexer using the three-waveguide interferometer is proposed and optimized in the design. The three-waveguide coupler was simulated by three dimensional BPM for analyzing the coupling including the bent region of the coupler, and the spectral characteristics of the proposed TWI was obtained by the transfer matrix method. The proposed TWI-triplexer has a feature of compact size compared to the common triplexers using cascaded MZIs, and can be fabricated by standard PLC fabrication processes. The proposed design shows low-loss as less than 1 dB for downstream channels, and 1.78 dB for upstream channel. The cross-talks for downstream channels are less than 13 dB even with a single stage of TWI, and it is expected that the crosstalk characteristics can be improved by cascading an additional stage of MZIs to the output ports.

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