The Numerical Simulation of a 8-Channel Optical Wavelength Division Multiplexer with Channel Spacing Δλ=0.8 nm

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Abstract: The numerical alaysis of optical device, silica-based device, are presented. The purpose of this paper is to simulate and to design a 8-channel optical wavelength division multiplexer(OWDM) based on Mach-Zehnder Interferometer(MZI) with wavelength spacing between channels Δλ=0.8 nm at central wavelength λ=1.55 μm. In initial condition for simulating, we assumed as follows. A channel waveguide is made from silica based P-doped SiO2 core layers in order to coupling with a fiber easily and its core dimension was 6 μm×6 μm. The core and clad index of channel waveguide were 1.455 and 1.444, separately, at λ=1.55 μm. Where, the separation between channel waveguides in coupling region was 3 μm. As a result of analysis, a group mode index of channel waveguide was 1.4498370, was gained by Hermite-Gaussian Method(HGM). Also, the channel spacing was determined by the waveguide arm length difference and was Δλ=0.8 nm as like a proposed condition. The central wavelength of a designed-multiplexer was activated about wavelength λ=1.55 μm, and we certificated that it can be used to 8-channel optical wavelength division multiplexer/demultiplexer.

Ⅰ. Introduction

The Wavelength Division Multiplexing(WDM) of optical signal is recently most important for increasing the information transmitting capacity per of a fiber in optical communication system. Many types of optical components for WDM and FDM systems have been proposed and system experiments using optical wavelength division multiplexers with as many as 10 wavelength channels have been demonstrated. These devices have been made by bulk component. They were fabricated on plannar film in order to integrate in the present day and various configurations for plannar (de)multiplexers have been accomplished by using optical interference filters, wavelength selective coupling, and optical diffraction gratings. Verbeek et al.[1] reported a weakly polarization-dependent 4-channel Mach-Zehnder demultiplexer(device length 33 mm) with a channel spacing of 7.7 nm, 2.6dB loss, and 16-dB channel crosstalk. Arjen R. Vellekoop et al.[2] reported a weak polarization-dependent 4-channel integrated optic wavelength demultiplexer(experimental device with 4.5×3.2 mm 2) with wavelength range 776.5-781.2 nm, channel spacing of 1.55 nm, 0.6dB of insertion loss for the central channels and 1.2dB for the outer channels for TE polarization, excluding 1.3dB waveguide propagation loss and crosstalk values measured 15.4-29.7dB for the TE and 13.4-22.2dB for the TM polarization. Hiroshi Takahashi et al.[3] reported a 16-channel wavelength multiplexer with 0.8nm of channel spacing in 1.55 μm band.

The purpose of this paper is to simulate and to design a 8-channel optical multiplexer with channel spacing Δλ=0.8 nm at central wavelength λ=1.55 μm band, that is an optical integrated circuit, capable of mass production by conventional Si IC-processing. Here, we present a simulation and characteristics of an integrated optical 8-channel wavelength division multiplexer based on Mach-Zehnder Interferometers, which has negligible reflections and low excess loss. The device is made from single mode channel waveguides of P-doped SiO_2 on Si, which have a very low(0.05dB/cm) waveguide loss for λ=1.55 μm band. Mach-Zehender Interferometers, both with Y-junctions as well as directional couplers, are often used in integrated optical devices such as phase modulators, optical frequency translators and signal processing application. Such active devices are usually made in Ti diffused $LiNbO_3$ making use of the electro-optical effect. Yasuji Murakami et al.[4] reported a optical directional coupler using deposited silica waveguides with 1.3dB/cm of waveguide transmission loss, 0.1dB of fiber to waveguide coupling loss, and 96% of power transfer. An integrated MZI consisting of silica-based waveguides is one of the most promising devices. Silica-based optical integrated circuits are fabricated on Si substrates by the combination of flame hydrolysis deposition and conventional photo-lithographic techniques followed by reactive ion etching. The flame hydrolysis deposition method is based on optical fiber fabrication processing.

The paper is organized as follows. Section II gives the transmission properties of a 8-channel multiplexer, the simulation results of multiplexer are described in Section III and conclusion is discussed in Section IV.

II. Analysis

The optical wavelength division multiplexer is device for (de)multiplexing, can be transmitted multi-channel informations with different wavelength at same time. The transmission characteristics of multiplexer(Fig. 1) can be described in terms of the propagation matrix of an individual Interferometers easily.

In Fig. 1, a single MZI is sketched and it has 2 input ports, two 3-dB directional couplers, and a central section where one of the waveguides is longer by ΔL in order to give a wavelength dependent phase shift between the two arms, and two output ports. For simplicity, we assume no waveguide- or bend losses in the present analysis.

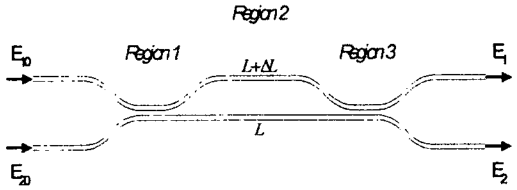


Fig 1. The structure of a Mach-Zehnder Interferometer.

From coupled mode equation[5-6] for the electrical field amplitudes E_1 and E_2, the propagation matrix for the coupler of length d has the form

$$M_{coupler} = \begin{bmatrix} \cos\delta d & i\sin\delta d \\ i\sin\delta d & \cos\delta d \end{bmatrix} \quad (2.1)$$

where, δ is the coupling coefficient and d is coupling length. This coefficient is related to the coupling length l_c for complete power transfer by $l_c = \pi/2$.

In the central region, the fields in both arms obtain a phase difference $k\Delta L$ (where $k = 2\pi n_{eff}/\lambda_0$, n_{eff} is a effective index of a waveguide and λ_0 is a wavelength of incident light) which is described by the matrix

$$M_{phaseshift} = \begin{bmatrix} e^{\frac{ik\Delta L}{2}} & 0 \\ 0 & e^{-\frac{ik\Delta L}{2}} \end{bmatrix} \quad (2.2)$$

The output fields, E_1 and E_2, are then given in terms of the input fields, E_{10} and E_{20}, by

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = M \cdot \begin{bmatrix} E_{10} \\ E_{20} \end{bmatrix} \quad (2.3)$$

where, $M = M_{coupler} \cdot M_{phaseshift} \cdot M_{coupler}$ is called the **propagation matrix** of a single MZI, is described by matrix

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (2.4)$$

with elements

$$M_{11} = \cos^2\delta d \cdot e^{\frac{ik\Delta L}{2}} - \sin^2\delta d \cdot e^{-\frac{ik\Delta L}{2}}$$
$$M_{12} = i2\sin\delta d\cos\delta d\cos(ik\Delta L/2)$$
$$M_{21} = i2\sin\delta d\cos\delta d\cos(ik\Delta L/2)$$
$$M_{22} = -\sin^2\delta d \cdot e^{\frac{ik\Delta L}{2}} + \cos^2\delta d \cdot e^{-\frac{ik\Delta L}{2}}$$

For perfect operation, we selected a coupling length by $d = l_c/2$, ie, $\delta d = \pi/4$ in order to become a 3-dB coupler in coupling region and inject light in a port 1 by E_{10}, then output fields, E_1 and E_2 are reduced to

$$E_1 = iE_{10}\left[\sin\left(\frac{k\Delta L}{2}\right)\right] \quad (2.5a)$$

$$E_2 = iE_{10}\left[\cos\left(\frac{k\Delta L}{2}\right)\right] \quad (2.5b)$$

Hence, the power transmission can be written in terms of the input powers P_{10} and P_{20}, is given by

$$P_1 = E_1E_1^* = P_{10}\sin^2\left(\frac{k\Delta L}{2}\right) \quad (2.6a)$$

$$P_2 = E_2E_2^* = P_{10}\cos^2\left(\frac{k\Delta L}{2}\right) \quad (2.6b)$$

and Transmission ratio $T_{10\to 1}$ from port P_{10} to P_1 and transmission ration $T_{10\to 2}$ from port P_{10} to P_2 are written as follows.

$$T_{10\to 1} = \frac{P_1}{P_{10}} = \sin^2 Kf \quad (2.7a)$$

$$T_{10\to 2} = \frac{P_2}{P_{10}} = \cos^2 Kf \quad (2.7b)$$

where, $K = \pi n_{eff}\Delta L/c$.

For an ideal Mach-Zehnder interferometer, with $k\Delta L = n\pi$ (n:integer) optical energy crosses over if n is even and goes straight through if n is odd. ie, maximum transmission ratio between two waveguides is gained at $\Delta f = \pi/2K = c/(2n_{eff}\Delta L)$. The transmission characteristics are graphed in Fig 2. This transmission characteristic is become a background for applicable possibility as wavelength division multiplexer.

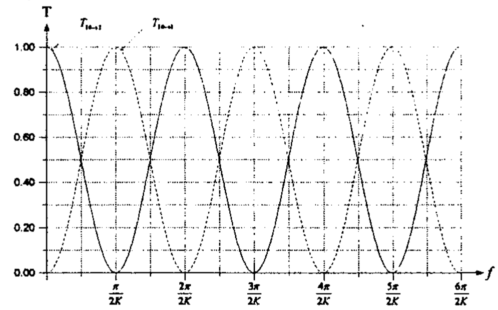


Fig 2. The transmission characteristics for frequency in MZI

III. The simulation results

In this chapter, we simulate a proposed 8-channel (de)multiplexer for optical wavelength division and its structure is sketched in Fig 3.

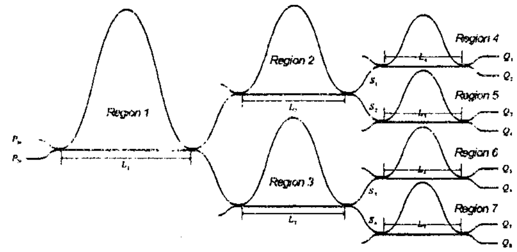


Fig 3. The structure of a 8-channel multiplexer.

It is consisting of 7 MZIs with a different length of optical path. Then, path difference in region 1 is longer two times than next region in order to have a double phase variation for wavelength. The structure can be analyzed by single 2 channel MZI separately and the M matrix in each region can be described by multiplying of propagation matrix for a 3dB coupler and phase term in central region. According to (2.4), M matrix is written by

$$M = \begin{bmatrix} M_{11}^{r} & M_{12}^{r} \\ M_{21}^{r} & M_{22}^{r} \end{bmatrix} \qquad (3.1)$$

with elements:

$$M_{11}^{r} = i\sin(k\Delta L_r/2)$$
$$M_{12}^{r} = i\cos(k\Delta L_r/2)$$
$$M_{21}^{r} = i\cos(k\Delta L_r/2)$$
$$M_{22}^{r} = -i\sin(k\Delta L_r/2)$$

where, r is a selected region index.

If we assume that optical power is injected only one port P_{10}, then the propagation matrix of single MZI using (3.1) is described by

$$\begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = \begin{bmatrix} M_{11}^{1} & M_{12}^{1} \\ M_{21}^{1} & M_{22}^{1} \end{bmatrix} \begin{bmatrix} P_{10} \\ 0 \end{bmatrix} \qquad (3.2)$$

Then, a propagation matrix of 8-channel multiplexer in region 2 and in region 3 of Fig. 3 using propagation matrix of single MZI in (3.2) is described by

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} M_{11}^{2} & M_{12}^{2} & 0 & 0 \\ M_{21}^{2} & M_{22}^{2} & 0 & 0 \\ 0 & 0 & M_{11}^{3} & M_{12}^{3} \\ 0 & 0 & M_{21}^{3} & M_{22}^{3} \end{bmatrix} \begin{bmatrix} 0 \\ R_1 \\ R_2 \\ 0 \end{bmatrix} \qquad (3.3)$$

So, a propagation matrix of 8-channel multiplexer in region 4~7 of Fig. 3 using propagation matrix of single MZI in (3.3) is described by

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \\ Q_7 \\ Q_8 \end{bmatrix} = \begin{bmatrix} M_{11}^{4} & M_{12}^{4} & 0 & 0 & 0 & 0 & 0 & 0 \\ M_{21}^{4} & M_{22}^{4} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{11}^{5} & M_{12}^{5} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{21}^{5} & M_{22}^{5} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{11}^{6} & M_{12}^{6} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{21}^{6} & M_{22}^{6} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & M_{11}^{7} & M_{12}^{7} \\ 0 & 0 & 0 & 0 & 0 & 0 & M_{21}^{7} & M_{22}^{7} \end{bmatrix} \begin{bmatrix} 0 \\ S_1 \\ S_2 \\ 0 \\ 0 \\ S_3 \\ S_4 \\ 0 \end{bmatrix} \qquad (3.4)$$

Converting electric fields to optical energies, the transmission characteristics of optical energy are described by $P_{10\to1} = \sin^2(k\Delta L_1/2)$ and $P_{10\to2} = \cos^2(k\Delta L_1/2)$. Where, $P_{10\to1}$ is optical energy goes through straight waveguide, $P_{10\to2}$ is optical power cross over from waveguide to the other waveguide, and $k\Delta L_1/2$ is phase difference due to optical path difference. This formation means that outgoing port was changed with period π according to phase variation element ($k\Delta L/2$) by wavelength. Hence, the channel spacing is determined by period $k\Delta L_1 = \pi$, outgoing port was changed in region 1. The path difference ΔL_1 in region 1 is determined by

$$k\Delta L_1 = 2\pi n_{eff}\frac{\Delta\lambda}{\lambda^2}\cdot\Delta L_1 = \pi \qquad (3.5\text{-a})$$

$$\Delta L_1 = \frac{\lambda^2}{2n_{eff}\Delta\lambda} \qquad (3.5\text{-b})$$

(3.5) is a approximated calculation by neglecting of variation of the mode refractive index in accordance with wavelength. The calculated mode index by Hermite-Gaussian Method[7] and optical path difference by (3.5) in interferometer MZI_1 with 0.8 nm of channel spacing in region 1 for high refractive index silica waveguide (6 μm×6 μm, Δn=0.75%, n_{core}=1.455, n_{clad}=1.444 for coupling with a fiber) is determined by 1.449837 and ΔL_1 = 1035.409446 μm. The MZI_2 and MZI_3 can be designed by similar to MZI_1 and the path difference must be calibrated in order that coupling wavelength period may become two times than MZI_1. It is designed with MZI_2 and MZI_3 having nearly the same spectral period but with peaks in the output interleaved. This was achieved by decreasing ΔL_2 of MZI_2 so that $k\Delta L_3 = k\Delta L_2 + \pi/2$ or

$$\Delta L_3 - \Delta L_2 = \frac{\lambda}{4n_{eff}} \qquad (3.5)$$

The path difference ΔL_3 is determined by

$$\Delta L_3 = \frac{\Delta L_1}{2} \qquad (3.6)$$

Path difference ΔL_2 and ΔL_3 are calculated at 517.4374518490 μm, 517.7047232601 μm.

The MZI_4, MZI_5, MZI_6, and MZI_7 can be designed by similar to MZI_2, MZI_3 and achieved by decreasing ΔL_4, ΔL_5, ΔL_6 so that

$$\Delta L_4 - \Delta L_7 = \frac{\lambda}{8n_{eff}}, \quad \Delta L_5 - \Delta L_7 = \frac{3\lambda}{8n_{eff}}$$

$$\Delta L_6 - \Delta L_7 = \frac{2\lambda}{8n_{eff}}, \quad \Delta L_7 = \frac{\Delta L_3}{2} = \frac{\Delta L_1}{4} \qquad (3\text{-}7)$$

Path difference ΔL_4, ΔL_5, ΔL_6, ΔL_7 are calculated at 258.690348 μm, 258.423106 μm, 258.556727 μm, 258.823969 μm respectively. In the case of coupler[8-9], it is very important components in the fabrication of various optical devices. It is need of bending waveguide, as the form of alphabet 'S', generally, so we should be noted here that the coupling phenomena takes place not only in the straight coupling region but also in the curved regions. Therefore, the coupling length l is an effective straight coupling length, which includes the entire mode-coupling effect in the straight and curved coupling region[8]. It was solved by step approximation as Fig 4, where, the total propagation matrix of this structure is described by multiplying propagation matrix in each partial waveguide pair. Total coupling length of 3-dB coupler, gained by effective index method, is 626.5 μm, and coupling length of bending region is 90.5 μm. Thus, we gained a length of straight coupling region by 510 μm using method, subtract coupling length by bending from total coupling length.

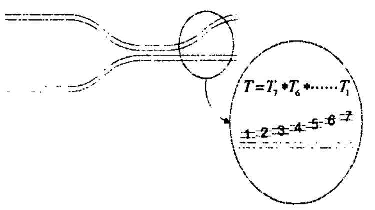
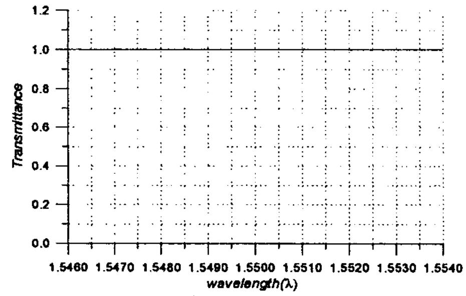
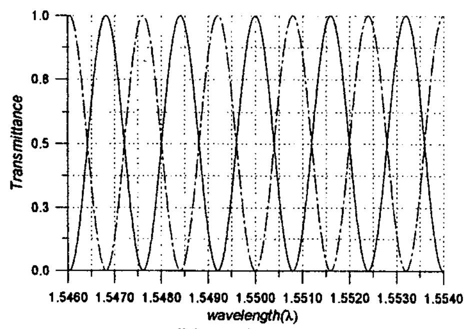


Fig 4. The step approximation for bending region.

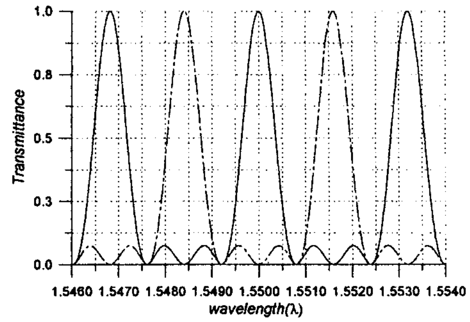
We next simulated a 8-channel multiplexer as a optical wavelength demultiplexing device by Finite Differential Beam Propagation Method(FD-BPM) using above results. The resulted transmittance in accordance with path difference for wavelength is graphed in Fig 5. Where, solid line is left port-outgoing power and dashed line is right port-outgoing power in each region. Fig 5(a) is input power for simulation and Fig 5(b)~(h) are results in interferometer 1~7. The resulting wavelength of channels are Q_1=1.5500 μm, Q_2=1.5532 μm, Q_3=1.5516 μm, Q_4=1.5484 μm, Q_5=1.5492 μm, Q_6=1.5524 μm, Q_7=1.5476 μm and Q_8=1.5508 μm, respectively. It shows that the channel spacing is 0.8nm. And, it is clear that for ideal 3-dB couplers and exact resonance wavelengths the crosstalk is negligible.



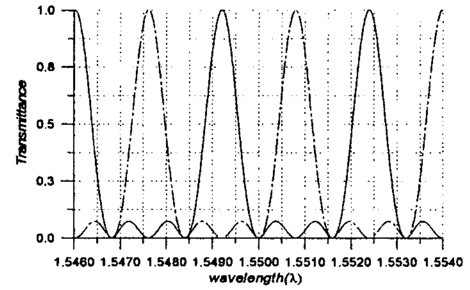
(a) input power



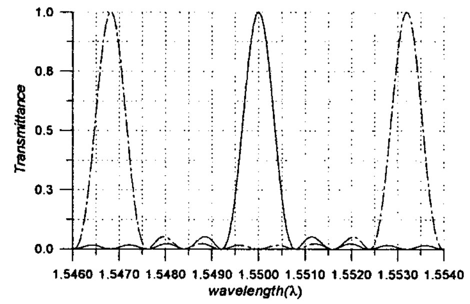
(b) region 1



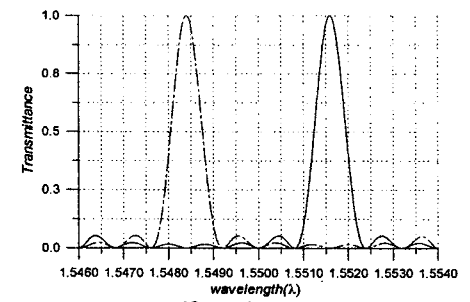
(c) region 2



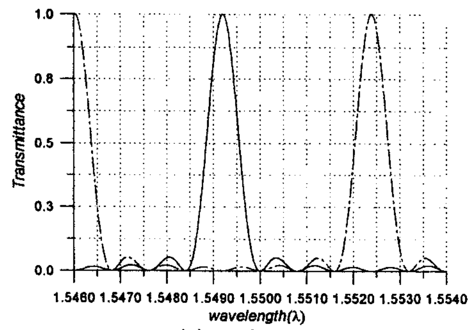
(d) region 3



(e) region 4



(f) region 5



(g) region 6