Comparison of characteristic of two and three couplers Mach-Zehnder interferometers paper

by Mark Finne

Comparison of Characteristic of Two and Three Couplers Mach-Zehnder Interferometers

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Abstract*—Mach–Zehnder Interferometer (MZI) is used to measure the phase shift (Δϕ) between two light beams related to relative length difference (ΔL) of MZI's two arms. The phase shift of the interferometer output is represented by output Free Spectral Range (FSR). Thus the FSR can be configured by setting its length difference of the two arms, to vary the phase shift. In this paper, the FSR of two couplers MZI are compared with three couplers MZI with two configurations based on the two couplers MZI's length difference. Length difference of the two couplers MZI is utilized for both of the length differences for the first configuration of three couplers MZI. As for the second configuration, each of the three couplers MZI length differences is half of the two couplers MZI length difference. The two couplers MZI are designed to have FSR at 10 nm, which can be obtained by using 0.166 mm as the length difference. 3 dB couplers are used for all of the configurations. Only one input port is utilized and the outputs are simulated in a normalized graph form. The MZIs simulation shows that the FSR of three couplers MZI first configuration is 5 nm, half of the FSR of two couplers MZI, while the FSR of three couplers MZI second configuration is 10 nm, the same as the FSR of two couplers MZI.

Keywords-Free Spectral Range, length difference, Mach-Zehnder Interferometer.

I. INTRODUCTION

With the advancement of telecommunication technology, a medium that can transmit a high amount of data with fast speed and affordable cost is needed. To fulfill this demand data should be transmitted in optical form [1]. There are several medium that can be used to transmit light, the medium used in this paper is Optical Fiber.

Light is a type of Electromagnetic waves (EM waves), the way light propagate through Optical Fibers follows the EM waves characteristic. Light in Optical Fibers can be divided or combined using optical switches, several Optical Switches can be used to make a filter, sensor, multiplexing, or interferometer [2].

There are several experiments about interferometer, for example: double slit Young experiment, Michelson interferometer, and Mach-Zehnder Interferometer (MZI) [3]. This paper will talk about MZI in several configurations.

MZI is a device made of several couplers connected together at the input and output ends by beam splitting and beam–combining optical couplers [4]. One of the arms between the couplers will be used as Reference arm, while the other arm will have longer length thus causing delay; these two arms are called Phase Shifter Region.

The outputs of MZI are determined by the coupler's coupling coefficient, the coupler's coupling length, the coupler's coupling distance, and the Phase Shifter Region's length difference. The only parameter that can be easily manipulated is the length difference. The length difference will cause delay in the Phase Shifter Region, thus making the power output phase in the output ports to shift; the phase shift will determine the power output's Free Spectral Range (FSR). By utilizing the length difference, MZI can be configured as filter or add/drop multiplexer.

Fig. 1 shows the diagram of two couplers MZI with 50/50 (3 dB) coupler's ratio and the optical fiber used is SMF-28. The length difference in the Phase Shifter Region is determined by using FSR equation.

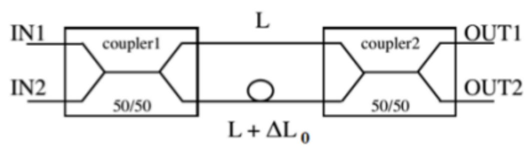

Fig. 1. Diagram of two couplers MZI [5]

The purpose of this paper is to design a two couplers MZI with a specific FSR and center wavelength, then add one couplers with the same Phase Shifter Region specification to form a three couplers MZI. The FSR of the two and three couplers MZI will be compared.

The two couplers MZI have FSR at 10 nm and center wavelength at 1550 nm, which can be obtained by using length difference (ΔL_0) at 0.166 mm.

By using the length difference obtained from the FSR equation, the comparison of two couplers MZI and three couplers MZI will be done in two configurations. In the first configuration, 0.166 mm will be applied for all of the three couplers MZI Phase Shifter Region length difference.

In the second configuration, the three MZI Phase Shifter Region length difference is obtained from 0.166 mm divided by the number of Phase Shifter Region, where in the three couplers MZI there are two Phase Shifter Regions. The input port that will be used is input port 1.

As far as the writer knows, there are no other studies with similar methodology and configuration as this paper.

This paper will simulate the MZI with these specifications:

Table I. Simulation Specification

Optical Fiber Type	Corning SMF-28
Core Refractive Index	1.4504
Cladding Refractive Index	1.4447
Core Diameter	8.3 µm
Couplers Power Output Configuration	50%/50% (3 dB)
Separation Between the Fiber Axes	7 µm
Center Wavelength	1550 nm
FSR	10 nm

II. THEORY

To simplify the analysis of MZI, the structure of MZI will be divided into three main parts: the first coupler, the Phase Shifter Region, and the second coupler. These three main parts will be represented in the form of transfer matrix. For the couplers component, the transfer matrix is [7]:

$$M_c = \begin{bmatrix} \cos(\Phi) & -j\sin(\Phi) \\ -j\sin(\Phi) & \cos(\Phi) \end{bmatrix} \quad (1)$$

Where $\Phi = k*z$, k is the coupling coefficient, and z is the coupler length.

Because every coupler used in this paper has 3 dB configurations, the value of $k*z$ should be $\pi/4$, thus the transfer matrix for the couplers is [7]:

$$M_c = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix} \quad (2)$$

For the Phase Shifter Region, the transfer matrix is [7]:

$$M_{\Delta\phi} = \begin{bmatrix} \exp(j\Delta\phi) & 0 \\ 0 & \exp(-j\Delta\phi) \end{bmatrix} \quad (3)$$

Where $\Delta\phi = \beta * \Delta L$, ΔL is the length difference between the two arms, and β is the propagation constant of the optical fiber. To simplify the equation, the phase shift will be represented as:

$$a = \frac{\Delta\phi 1}{2} \quad (4)$$

$$b = \frac{\Delta\phi 2}{2} \quad (5)$$

Where a represent delay in the first Phase Shifter Region and b represent delay in the second Phase Shifter Region. The value of propagation constant β in the Phase Shifter Region equation can be calculated by using the bisection method on the characteristic equation of LP_{01} mode [7]:

$$\frac{J_0(u)}{u \cdot J_1(u)} = \frac{K_0(w)}{w \cdot K_1(w)} \quad (6)$$

Where J is the Bessel Function of the first kind and K is the Modified Bessel Function of the second kind. While u and w are the wave numbers.

A. *Two Couplers MZI*

The transfer matrix for two couplers MZI is [8]:

$$M_1 = M_c \cdot M_{\Delta\phi} \cdot M_c \quad (7)$$

By inserting the Phase Shifter Region and the couplers matrix, the transfer matrix for two couplers MZI is:

$$M_1 = j \begin{bmatrix} sin(a) & -cos(a) \\ -cos(a) & -sin(a) \end{bmatrix} \quad (8)$$

The output amplitude can be described by:

$$E_{out} = M \cdot E_{in} \quad (9)$$

Where the normalized input in Equation (9) matrix at one port is represented as:

$$E_{in} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (10)$$

Then by substituting Equations (8), (9), and (10), the outputs for two couplers MZI with one input are [9]:

$$E_{out1} = \frac{j}{\sqrt{2}} \sin(a)$$
$$E_{out2} = -\frac{j}{\sqrt{2}} \cos(a) \quad (11)$$

The power outputs equations can be obtained from Equation (11):

$$P_{out} = |E_{out}|^2 \quad (12)$$

$$P_{out1} = \frac{1}{2}\sin^2(a)$$
$$P_{out2} = \frac{1}{2}\cos^2(a) \quad (13)$$

Equation (13) will be simulated using the specification listed in Table I, the simulation result is in the form of MZI normalized power output.

B. Three Couplers MZI

For three couplers MZI, the transfer matrix can be derived by using the same method as two couplers MZI and adding the third coupler matrix. The transfer matrix for three couplers MZI is:

$$M_2 = M_1 \cdot M_{\Delta\phi 2} \cdot M_c \tag{14}$$

By inserting the phase shift, the couplers, and two couplers MZI matrix, the transfer matrix for three couplers MZI is:

$$M_2 = \frac{\sqrt{2}}{2}\begin{bmatrix} M_{211} & M_{212} \\ M_{221} & M_{222} \end{bmatrix} \tag{15}$$

Where

$$\begin{aligned} M_{211} &= j\sin(a+b) - \cos(a-b) \\ M_{212} &= -j\cos(a+b) + \sin(a-b) \\ M_{221} &= -j\cos(a+b) - \sin(a-b) \\ M_{222} &= -j\sin(a+b) - \cos(a-b) \end{aligned} \tag{16}$$

By using the same method from two couplers MZI transfer matrix, the outputs for three couplers MZI with one input are:

$$\begin{aligned} E_{out1} &= \frac{\sqrt{2}}{2}(j\sin(a+b) - \cos(a-b)) \\ E_{out1} &= -\frac{\sqrt{2}}{2}(j\cos(a+b) + \cos(a-b)) \end{aligned} \tag{17}$$

Just like the two couplers MZI, the power outputs equation are:

$$P_{out} = |E_{out}|^2 \tag{18}$$

$$\begin{aligned} P_{out1} &= \frac{1}{2}\left(\sin^2(a+b) + \cos^2(a-b)\right) \\ P_{out2} &= \frac{1}{2}\left(\cos^2(a+b) + \cos^2(a-b)\right) \end{aligned} \tag{19}$$

Equation (19) will be simulated using the specification listed in Table I, the simulation result is in the form of MZI normalized power output.

C. Free Spectral Range (FSR)

To length difference used in this paper is calculated by using the FSR equation for two couplers MZI [9]:

$$FSR = \frac{\lambda_c^2}{n_{eff}\Delta L} \tag{20}$$

Where λ_c is the center wavelength and n_{eff} is the effective refractive index.

Using Equation (20), the length difference needed for two couplers MZI with FSR = 10 nm at center wavelength 1550 nm is calculated to be 0.166 mm.

III. Simulation and Analysis

The two and three couplers MZI will be simulated by using the specification listed in Table 1 and the length difference found from the FSR equation.

A. Two Couplers MZI

The length difference 0.166 mm obtained from FSR at 10 nm is applied into the two couplers MZI power equation to obtain the normalized power outputs. The simulation result of Equation (13) is shown in graph bellow.

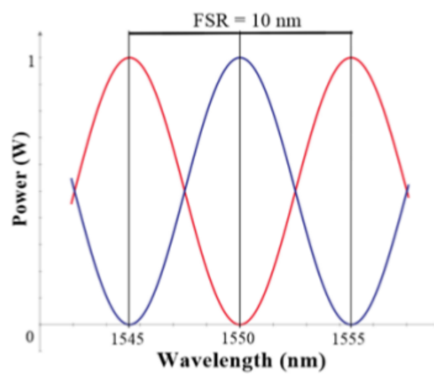

Fig. 2. Two couplers MZI normalized power output spectral response graph (Pout1 = blue, Pout2 = red)

The result of two couplers MZI simulation in Fig. 2 shows that the FSR is at 10 nm with wavelength range 1545-1555 nm with center wavelength 1550 nm. The FWHM of two couplers MZI is 3.3 nm.

B. Three Couplers MZI

The length difference 0.166 mm obtained from FSR at 10 nm is substituted into the applied into three couplers MZI power equation with two configurations. In the first configuration, 0.166 mm will be applied for all of the three couplers MZI Phase Shifter Region length difference, while in the second configuration, the length difference is obtained from dividing 0.166 mm by the number of Phase Shifter Region of the three couplers MZI, where in the three couplers MZI there are two Phase Shifter Regions. Fig. 3 shows the diagram of the three couplers MZI two configurations used in this paper.

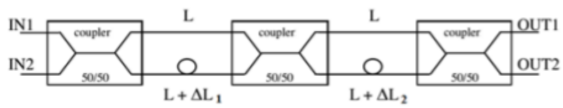

Fig. 3. Diagram of three couplers MZI configuration, in the first configuration the length difference is $\Delta L_0 = \Delta L_1 = \Delta L_2$, while in the second configuration the length difference is $\Delta L_0 = \Delta L_1 + \Delta L_2$.

The three couplers MZI will use Equation (19) to find the normalized output power in the form of graph. The simulation result for the three couplers MZI first configuration is shown in Fig. 4 below:

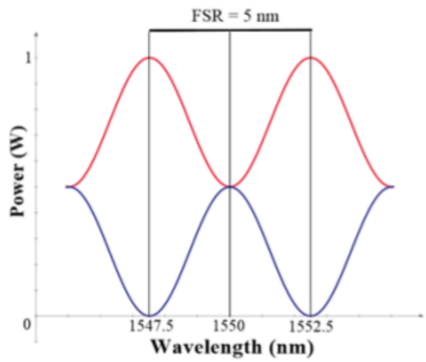

Fig. 4. Three couplers MZI first configuration power output spectral response graph (Pout1 = red, Pout2 = blue)

The result of two couplers MZI simulation in Fig. 4 shows that the FSR is at 5 nm with wavelength range 1547.5-1552.5 nm with center wavelength 1550 nm. The FSR is half of the two couplers MZI FSR. The graph shows that the FWHM is 3.3 nm, the same as two couplers MZI FWHM.

The simulation result for the three couplers MZI second configuration is shown in Fig. 5 below:

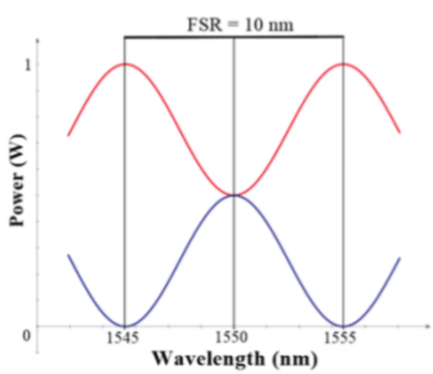

Fig. 5. Three couplers MZI second configuration normalized power output spectral response graph (Pout1 = red, Pout2 = blue)

The result of three couplers MZI second configuration shows that the FSR is at 10 nm with wavelength range 1547.5-1552.5 nm with center wavelength 1550 nm. The graph shows that the FWHM is 3.3 nm, the same as two couplers MZI FWHM.

The combined graph for the first and second configuration is shown in figure below:

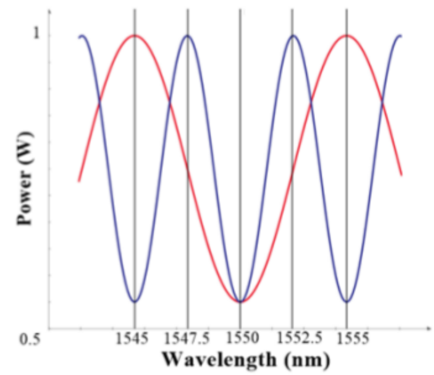

Fig. 6. Three couplers MZI first and second configuration (First configuration = red, second configuration = blue)

The simulation result in Fig. 2, 4, and 5 shows that the power outputs of both first and second configuration of three couplers MZI are divided into two amplitude ranges, where at one output port the minimum value doesn't reach zero, while the other output port maximum value is half of the input.

The data obtained from simulation of two and three couplers MZI with two configurations are presented in table below:

Table II. Two and Three couplers MZI Simulation Data

	Two couplers MZI	Three couplers MZI	
		First Configuration	Second Configuration
FSR	10 *nm*	5 *nm*	10 *nm*
Wavelength Range	1545 – 1555 *nm*	1547.5 – 1552.5 *nm*	1545 – 1555 *nm*
Center Wavelength	1550 *nm*	1550 *nm*	1550 *nm*
FWHM	3.3 nm	3.3 nm	3.3 nm

The table shows that the FSR of the first configuration is half of the two couplers MZI's FSR, the FSR difference is caused because more delay applied in the Phase Shifter Region, thus the output phase is shifted and decreasing the FSR.

In the second configuration, the FSR is the same as the two couplers MZI's FSR. The delay in the Phase Shifter Region is lower than the first configuration, thus causing the phase and FSR of the output match the two couplers MZI. The FWHM of two couplers MZI are the same as both of three couplers MZI configurations.

IV. Conclusion

We have presented characteristics of two and three couplers MZI with two configurations. The MZIs simulation shows that the FSR of three couplers MZI first configuration is 5 nm, half of the FSR of two couplers MZI. For the second configuration the FSR is 10 nm, the same as the FSR of two couplers MZI and double the FSR of three couplers MZI first configuration. Even though the FSR of two couplers MZI and three couplers MZI second configuration are similar, three couplers MZI has more loss than two couplers MZI. We haven't include the loss from the coupler and the optical fiber into the simulation, thus the simulation result can't show all of FSR differences of the two and three couplers MZI. An experiment with precise equipment coupled with the simulation will provide better comparison between two couplers MZI and three couplers MZI second configuration, including the advantages and disadvantages of both MZIs.

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