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# Mach Zehnder Interferometer and its Applications

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## ABSTRACT

This paper describes the design of Mach Zehnder Interferometer and reviews its applications in emerging optical communication networks. Mach Zehnder Interferometer is basically used to measure relative phase shift between two collimated beams from a coherent light source. Using this basic principle a number of devices can be designed, few of these such as optical sensors, all-optical switches, optical add-drop multiplexer and modulator are discussed in this paper.

## Keywords

Mach Zehnder Interferometer (MZI), optical communication systems, all-optical devices, Wavelength Division Multiplexing (WDM).

## I. INTRODUCTION

There has been an incredible growth within the contribution and capability of fiber optic communication networks over the past twenty-five years. This growth has been possible by the development of new optoelectronic technologies that are utilized to exploit the enormous bandwidth of optical fiber. Today, systems are available which operate at bit rates in excess of 100 Gb/s. Optical signal is now a dominant carrier for worldwide information transmission. It has the capability to fulfill the demand of high speed and bandwidth for future networks. Several of the advances in optical networks have been made possible by the use of Mach Zehnder Interferometer. Mach Zehnder interferometric devices are employed in optical processing of signals like switching, add-drop multiplexing, modulators etc. All these devices are needed for ultra fast signal processing in optical domain without the requirement of converting them to electronic signals and back to optical signal. In this paper, Section 2 and 3 deals with the basics and design of MZI respectively. In section 4 applications of MZI are discussed and section 5 gives the conclusion.

## 2. MZI BASICSs

MZI is a device used to determine relative phase shift between two collimated beams from a coherent light source either by changing length of one of the arms or by placing a sample in path of one of the beams.MZI has two input ports and two output ports. A basic MZI [1] as shown in Fig.1 is constructed using two couplers, one at the input acts as splitter and another at the output acts as combiner. The light is split in two arms of the interferometer by the input coupler and recombined at the output by the output coupler. The optical path length of two arms is unequal making the phase shift corresponding to delay to be a function of wavelength of the input signal. This property is used to design a number of all-optical devices used for signal processing in all-optical domain.

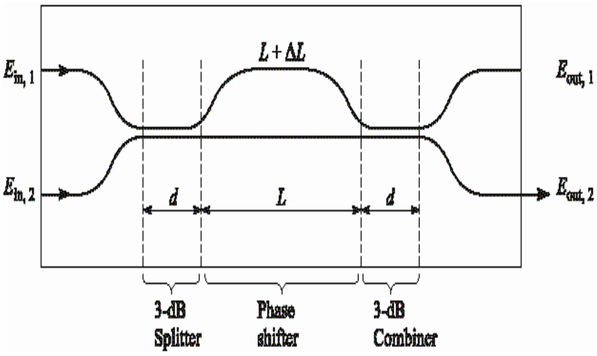


**Fig.1: An MZI constructed by interconnecting two 3dB directional couplers [1]**

## 3. MZI DESIGN

In this part, the basic design of Mach Zehnder Interferometer is proposed. Design parameters used are listed in Table 1. Figure 2 shows the design layout of MZI, designed and simulated with the OptiBPM layout designer.

**Table 1. MZI Design Specifications**

| | |
|---|---|
| **Dielectric Materials** | |
| Name: Core<br>Refractive Index:1.49 | Name: clad<br>Refractive Index:1.48 |
| **Channel Profile**: Channel Pro1 | |
| **Wafer Properties** | |
| Wafer dimensions(in μm)<br>Length:3000<br>Width:100<br>Wafer profile: clad | |

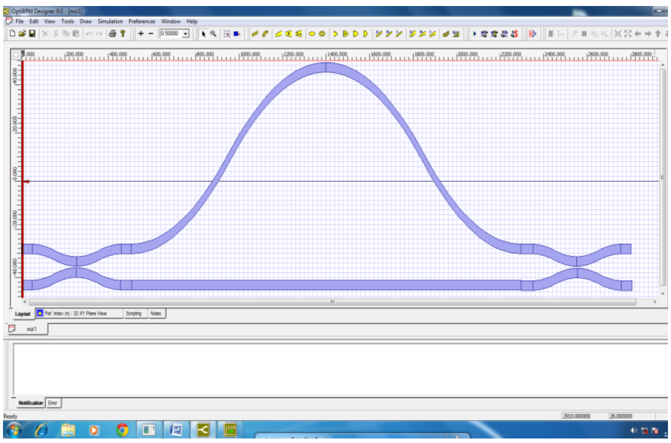

**Fig.2: MZI design layout.**

Simulation is carried out at 1.30 µm wavelength using 2D isotropic simulation. Input field is selected as modal. Other possible fields are rectangular and Gaussian. Optical field propagation is as shown in fig.3.

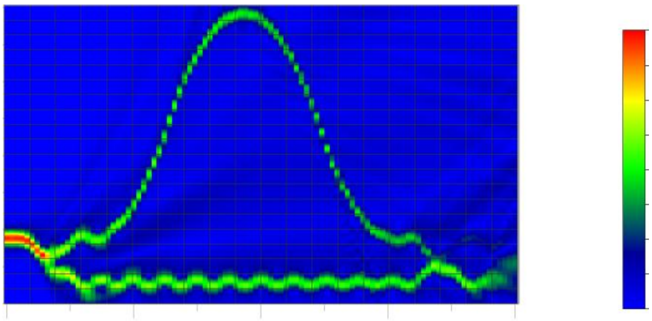

**Fig.3: Optical field propagation in MZI as observed in OptiBPM Analyzer.**

# 4. APPLICATIONS

## 4.1 Mach Zehnder Interferometer as sensors

Optical fiber sensors have attracted great attention in recent years due to their advantages such as immunity to electromagnetic interference, resistance to erosion, high sensitivity, low propagating loss, high accuracy and can work in contact with explosives. These include sensors used in the measurements of the liquid level, refractive index (RI), temperature, strain and others. Recently, optical fiber Mach–Zehnder interferometer (MZI) sensors have attracted a lot of interest for various physical and chemical sensing applications due to their simple structure, capability of responding to a variety of measurands, ease of fabrication, and low cost [2].

Basic technique of using MZI as sensor is as shown in Fig.4. MZI has two arms, one used as sensing arm and another used as reference arm [2].The sensing arm is exposed to external variations such as temperature, refractive index, strain etc. while reference arm is kept isolated from variations. Combined output at the MZI output port has the interference component according to the optical phase difference between two arms. The change induced in the sensing arm by any of the measurands changes the optical phase difference of the MZI, which can be easily detected by analyzing the variation in the interference signal.

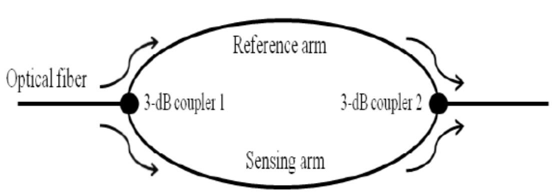


**Fig.4: The schematic of an MZI sensor [2]**

After the invention of long periodic fiber gratings (LPGs), the scheme of using conventional MZI as sensor was rapidly replaced by in-line waveguide interferometer [2]. Figure 5 describes various types of in-line MZI sensors. Figure 5(a) shows one of the method in which a part of the beam carried in the core of a fiber is coupled to the cladding of the same fiber by the first LPG and then recoupled into the core by second LPG. The uncoupled beam and the combined beam in the core produce an interference pattern thus producing a very effective in-line MZI. This MZI has the same physical path length in both sensing and reference arms but has different optical path lengths because of modal dispersion as the beam passing through cladding experiences refractive index which is different from that of the core.

Another way of making an in-line MZI is splicing two fibers with a minute lateral offset as shown in fig.5 (b). Due to this offset, a part of the beam in core is coupled to several cladding modes, independent of wavelength. An MZI can also be formed by fusion splicing a piece of Photonic Crystal Fiber (PCF) in between fibers with a small required deviation [3]. The offset method is fast and cost effective as compared to the grating method. By adjusting the amount of offset, number of involved cladding modes and insertion loss can be controlled.

Collapsing air holes of a PCF is another good method for splitting a light beam into core and cladding modes of a fiber. It is easy and does not need any troublesome cleaving or aligning process. The beam in core of a PCF is expanded at the air hole collapsed region, so that some of its part could be coupled to the cladding modes of PCF, as shown in fig.5(c).In this case, high insertion loss was observed compared to the offset method [2] and also core mode coupled to several cladding modes. Further, controlling the number of involved cladding modes was difficult. The insertion loss could be reduced by ~3dB by combining collapsing method and the grating pair method [2]. These PCF-based in-line MZI sensors have several advantages including operation in high temperatures and low cross sensitivity.

Most of the in-line MZIs are based on multimode interference. As the cladding part of a SMF is a multimode waveguide, the number of modes involved in interference is more than one. In-line MZIs using LPG pair are an exception which mostly makes use of a single cladding mode [5].Such involvement of multiple cladding modes affects the performance of sensor because the sensitivity of each mode is different to external variations. Therefore, analysis of the sensor performance should be made with MMI and the number of involved cladding modes should be minimized during sensor fabrication.

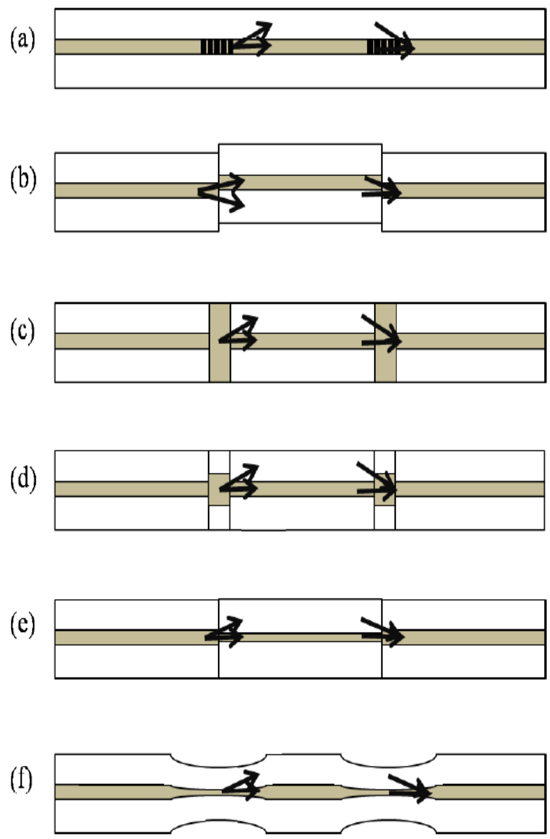


**Fig.5: Configuration of various types of in-line MZI sensors using (a) a pair of LPGs, (b) core mismatch, (c) air-hole collapsing of PCF, (d) MMF segment, (e) small core SMF, and (f) fiber tapering [2]**

Using fibers having different core sizes is another method for splitting the beam in core and cladding as shown in Fig. 5(d, e) [6, 7]. Figure 5(d) shows a method in which a small length of MMF is fusion spliced with SMF at two points along the SMF. In this case, the light propagating through the core of the SMF is spread at the MMF region and then coupled into the core and cladding of the next SMF [6]. Figure 5(e) shows another method, in which a fiber with a small core diameter is inserted between two conventional SMFs. At the small core fiber region, the beam is guided as the core mode and as well as the cladding mode [7].
Figure 5(f) shows an effective in-line MZI which is formed by tapering a fiber at two points along the fiber [8, 9]. The core mode diameter gets increased due to tapering and part of it can be easily coupled to the cladding mode(s).This method is relatively very simple and cost effective but mechanically weak especially at the tapering region. Besides these, MZIs are formed using double cladding fiber [10], micro-cavities [11], and a twin-core fiber [12]

## 4.2 Mach Zehnder Interferometer based OADMs

The main function of an OADM is to add and drop wavelengths (channels) to and from a fiber in wavelength division multiplexed optical networks. This operation possesses a substantial amount of potential applications like controlling, monitoring, combining and routing wavelengths [13].

There are two main types of OADM used in WDM networks: fixed OADMs that are used to add or drop signals on dedicated WDM channels and reconfigurable OADMs that have the ability to electronically change the selected channel routing through the optical network.
Figure 6 shows a Mach-Zehnder OADM using dual Bragg grating, one in each arm of the interferometer. The method was first proposed by D.C. Johnson et al. and later optimized by F. Bilodeau et al. [14, 15].The Mach Zehnder Interferometer comprises two fused 3dB couplers with the two arms of the MZI ideally equal. Two Bragg gratings are then written symmetrically in the two arms of MZI.

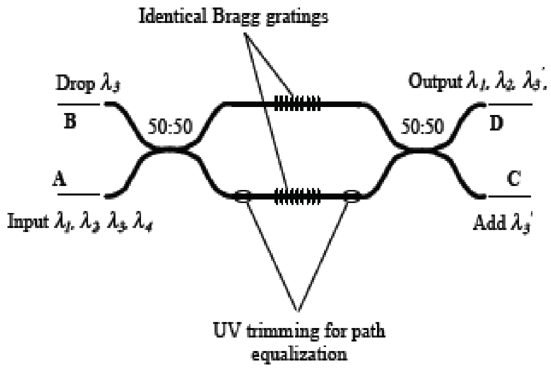


**Fig.6: Dual Bragg grating MZI OADM [14]**

The Bragg gratings are written with a resonant wavelength $\lambda_3$.The unaffected wavelengths ($\lambda_1$, $\lambda_2$, $\lambda_4$) ideally see a normal MZI, splitting the light at the first coupler and recombining at the second 3dB coupler. If the MZI is perfectly balanced, no light emerges from port C. $\lambda_3$ is also split by the first coupler but gets reflected by the two identical gratings. On reaching the first coupler, coherent recombination takes place and $\lambda_3$ exits the drop port [14]. Several channel OADMs can be formed by adding more gratings with different resonant wavelengths [15].
Couplers used in forming OADMs are polarization insensitive. UV trimming is used to balance the interferometer after gratings are written. UV trimming relies on photoinduced changes in the refractive index to adjust the optical path-length difference [16].The compact design makes the balance of the interferometer insensitive to ambient temperature fluctuations. The drift in the dropped wavelength is mainly due to the temperature sensitive Bragg gratings [15].
As the configuration depends on splitting and interference of light, it is highly sensitive to change in signal path length, matching of the couplers and characteristics of gratings being used. Therefore, environmental stabilization, UV trimming of individual paths, and identical couplers and gratings are essential for good device performance.
A unique method for manufacturing a Mach-Zehnder OADM was developed by S.Bethuys et al [17].Dual Bragg grating MZI-OADM was written in a twincore fiber. The special twincore fiber is used to improve the balance of the interferometer.
By optimizing the dual Bragg grating MZI OADM, a stable device with a channel isolation of more than 20dB, an insertion loss of less than 0.5dB and a channel spacing of less than 100 GHz (0.8 nm) is achievable [15]

## 4.3 Mach Zehnder Interferometer switches

The demand for faster communication is increasing day by day. To fulfill this demand, there is a need for higher and higher data rates which is possible only if data remains in optical domain. For this, advanced optical networks require all-optical ultrafast signal processing devices. Therefore, all-optical switches are now taking over the use of O-E-O switches. Monolithically integrated MZI switches represent the most promising solution due to their compact size, thermal stability and low power (few fJ for input signal and few hundred fJ for control pulse) operation. Figure 7 shows the basic 2X2 MZI switch structure in which two 3dB couplers are connected by equal length interferometric arms. The first coupler splits the signal into two beams which experience a phase difference while passing through the arms of interferometer. This phase difference is achieved by varying voltage across electrodes covering interferometric arms which in turn changes refractive indices. The output 3dB coupler combines both the beams having different phase and final outputs are observed as per constructive and destructive interference [18].The Lithium Niobate has been used to design switches based on Mach Zehnder Interferometer or directional coupler efficiently [19]. The symmetric Mach Zehnder Interferometer (MZI) has shown the better flexibility and shortest switching windows as compared to various configurations [20]. Improvement in all optical switching performance and high-speed capability of the MZI switches are investigated in [21, 22] respectively.

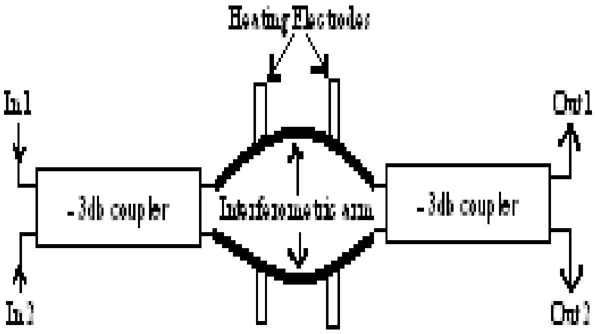


**Fig.7: Basic 2x2 MZI switch structure [19]**

Integrated Mach-Zehnder interferometers (MZIs) incorporating semiconductor optical amplifiers SOAs in the interferometer arms have recently been developed as very high-speed all-optical switching devices [23].Various SOA based switching configurations have been demonstrated, such as terahertz optical asymmetric demultiplexers (TOADs)[24],ultrafast nonlinear interferometers(UNIs)[25] and Mach Zehnder Interferometers[26-28], out of which MZI switches are most efficient.

An MZI with two SOAs in two branches(see Fig.8) can also demultiplex an OTDM signal at high speeds and can be fabricated in the form of an integrated compact chip using InGaAsP/InP technology [26,31].MZI switches have demonstrated single-channel OTDMs at up to 168Gb/s and might even be used for higher data rates[29-30].

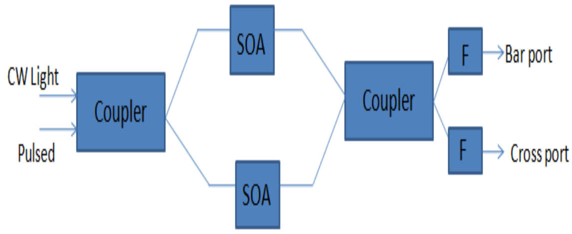


**Fig.8: SOA based MZI optical switch [23]**

MZI-SOA switch is utilized for designing a tree-net architecture in all-optical domain, which is successfuly exploited for all-optical logic and arithmetic operations (half-adder, half-subtractor, full-adder, full-subtractor, data comparator)[23]

## 4.4 Mach Zehnder Interferometer modulator

As the demand for high speed Communication is increasing, the need for external modulation in Optical transmission systems is also increasing. One of the possibilities of external modulation is to use a Mach-Zehnder structure in a material showing strong electro-optic effect(such as $LiNbO_3$).Mach Zehnder modulators provide both the required bandwidth and equally important means for minimizing the effects of dispersion which is one of the major factors for limiting the performance of high speed fibre-Optic transmission systems.

In Mach-Zehnder modulators, the incoming light is split into two arms of the interferometer. A voltage is applied to both the arms causing a change in their refractive index according to electro-optic effect. This changing refractive index phase modulates the beam propagating through arms of interferometer according to applied voltage. This phase modulation gets converted to intensity modulation by combining the two paths.

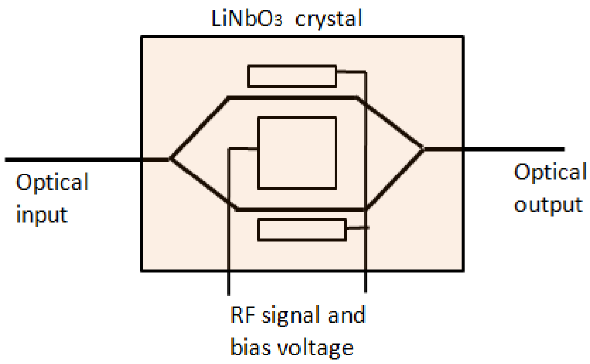


**Fig.9: Mach-Zehnder interferometer modulator**

$LiNbO_3$ has been the material of choice for electro-optic MZ modulator because it combines the desirable qualities of high electro-optic coefficient and high optical transparency in the near-infrared wavelength used for telecommunications [32] $LiNbO_3$ MZ modulator can operate satisfactorily over a wavelength range of 1300 – 1550nm. It has been widely used in today's high-speed digital fiber communication[33].$LiNbO_3$ MZ modulators with stable operation over a wide temperature range, very low bias-voltage drift rates, and bias-free operation are commercially available. High-speed, low-chirp modulators are needed to take advantage of the wide bandwidth of optical fibers [34]. Modulators have become a critical component both in the high-speed time-domain-multiplexing (TDM) and wavelength-division-multiplexing systems (WDM).Two basic types of configurations of the Mach-Zehnder Modulator are there-

### *4.4.1 Push-Pull Configuration*

This configuration is obtained by applying data and bias voltage in one arm and inverted data and inverted bias voltage in the other arm. This increases the relative phase shift in one path and decreases it in the other path. Since phase changes are equal in magnitude but opposite in sign in each arm a chirp free intensity modulation is obtained.

### *4.4.2 Asymmetric Configuration*

In this type of configuration, the modulating signal and the bias voltage are applied to only one of the interferometric branches, either to the same or to different branches.

## 5. CONCLUSION

In this paper an overview of Mach Zehnder Interferometer, its design and applications in Optical Communication networks is presented. MZI has great potential in practical applications and is capable of realizing many of the all-optical functions required in emerging optical networks. As optoelectronic integrated circuit technology advances and manufacturing cost decreases, the use of MZIs will expand.

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