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Design and Modelling of Mach-Zehnder Interferometer for Bio-Sensing Applications

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Abstract:
A Mach-Zehnder Interferometer can be used to precisely vary and measure very small phase shifts in a beam of coherent light. We are using it to find the refractive index of biological sample. The phase variations caused by a liquid sample can be measured by Mach-Zehnder Interferometer. An optical fibre Mach-Zehnder Interferometer measures the optical path length difference in the moving sample. The measurements can be performed in different liquids. The Mach-Zehnder Interferometer can be constructed for measuring the refractive index for different modes. Any sensor is designed for Single mode operation. The Mach-Zehnder Interferometer, as a high sensitive refractive index-sensor can be used to detect refractive index in the surrounding medium. Due to the high sensitivity towards refractive index, the Mach-Zehnder Interferometer is attracted towards chemical, biological and biochemical sensing applications.

1. INTRODUCTION:
Mach-Zehnder interferometer is a simple highly configurable device[1],[2],[3],used to demonstrate interference by division of amplitude[2]. Designing and modeling is safe and cost effective and includes only the fusion splicing[2],[3]. Especially useful in biological ,chemical and medical fields for local use[1],[2],[3],[4]. 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. 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.1.2. The Mach-Zehnder Interferometer consists of three different regions.
They are

(i) Splitter
(ii) Central Region
(iii) Combiner

The splitter divides the input signal into two output ports, which are connected to central region waveguides.The main function of Mach-Zehnder Interferometer provide wavelength dependent phase shift between the input signals, which are divided to the central region. The central region consists of two waveguides in which, one of them is longer by ΔL meters, as shown in fig:1.1. The two waveguides of Central region form the two arms of Mach-Zehnder Interferometer.

The two unequal arms of waveguides makes the phase shift corresponding to delay. This property is used to design a number of optical devices for signal processing in optical domain. Combiner combines the two signals at the output. The recombined signal will interfere constructively at one output port, and destructively at the other output port. The end result is the signal at only one output port.

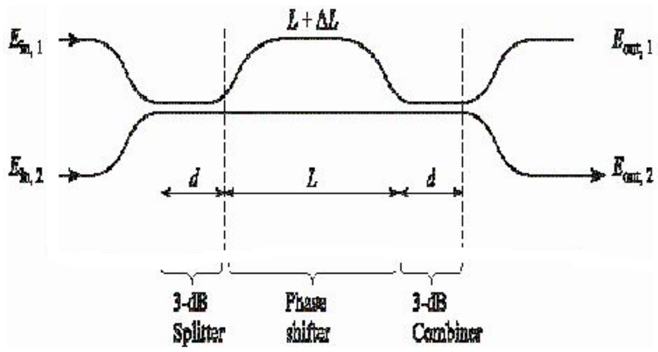

Figure 1.1:Schematic drawing of the Mach-Zehnder Interferometer

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The possibility to easily control the features of the light in the reference channel without disturbing the light in the object channel popularized the Mach–Zehnder configuration in holographic interferometry. In particular, optical heterodyne detection with an off-axis, frequency-shifted reference beam ensures good experimental conditions for shot-noise limited holography with video-rate cameras, vibrometry, and laser Doppler imaging of blood flow.

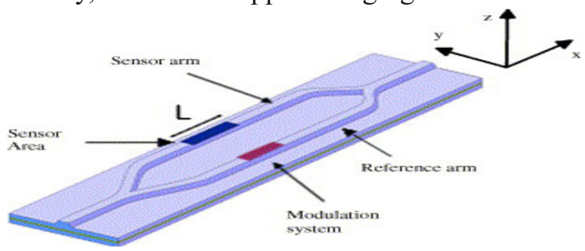

Figure 1.2: Cross-section of Mach-Zehnder Interferometer

1.2 OBJECTIVES OF PROJECT:

The main objectives of the project are

1. To design a Mach-Zehnder Interferometer for measurement of refractive index for biosensing applications.
2. The effect of light interaction with the fluid containing the bio-molecules will be studied.
3. To continuously monitor the loss of propagation and also increase the accuracy.

1.3 METHODOLOGY:

To achieve the required objectives of the project the following steps are used

» Finite element modelling (FEM) is performed for the Mach-Zehnder Interferometer using Bio-sensing Application.

» FEM simulations are accurate and flexible for detailed studies. FEM is considered as a three step process: preprocessing (mesh generation), analysis and post processing. With the help of FEM a complicated problem is divided into small elements that can be solved in relation to each other.

» In the design and modelling of Mach-Zehnder Interferometer, 3D modelling has been done which is more realistic and offers many advantages over 2D modelling.

» To study the effect of fundamental mode, higher order mode and its propagation through the waveguide.

» The effect of light interaction with the fluid containing the bio-molecules will be studied.

» The effect and applications of evanescent wave decaying in the cladding is studied.

2. PROPOSED SYSTEM:

In this project our primary objective is to model Mach-Zehnder Modulator as shown in Figure2. The input wave is launched into a directional coupler. The power of the input is split equally into the two output waveguides of the first directional coupler. Those two waveguides form the two arms of a Mach-Zehnder interferometer. On one of the arms, you can apply an electric field to modify the refractive index in the material and, thus, modify the phase for the wave propagating through that arm. The two waves are then combined into another 50/50 directional coupler.By changing the applied voltage you can continuously control the amount of light exiting from the two output waveguides. A common material for fabricating waveguide modulators is lithium niobate, LiNbO3. Lithium niobate is a ferroelectric crystal that exhibits uni-axial birefringence. Waveguide structures can be fabricated by either in diffusion of Ti into the core regions or by annealed proton exchange, where lithium ions are exchanged with protons from an acid bath.

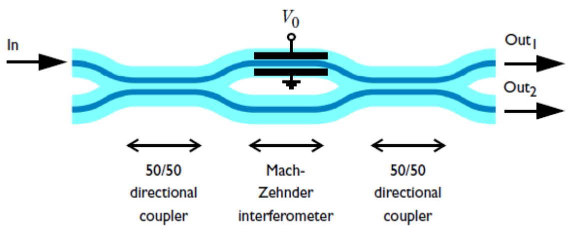

Figure 1.4 : Mach-Zehnder Interferometer

2.1 MATHEMATICAL MODELLING:

2.1.1 Model Definition:

2×2 Mach-Zehnder Interferometer(MZI) Multiplexer/modulator is shown in fig.3.1.It consists of three stages ,

1. 3db coupler at the beginning,it acts as splitter
2. A Central region consists of two waveguides in which one of them is longer by ΔL.

This provides a wavelength dependent phase shift is given by :

$$\Delta\Phi = 2\pi/\lambda[n2(\text{length of waveguide2}) - (\text{length of waveguide1})]$$

$$\Delta\Phi = 2\pi/\lambda[n2(L+\Delta L) - n1\ L]$$

Let refractive index of waveguides is equal i.e.., n1=n2=n

$$\Delta\Phi = 2\pi n/L(\Delta L)$$

$$K = 2\pi n/\lambda$$

$$\Delta\Phi = k\Delta L$$

Scattering matrix is defined by:

$$M_{\Delta\Phi} = \begin{pmatrix} S_{11} & S_{21} \\ S_{21} & S_{22} \end{pmatrix}$$

Scattering matrix for first and last 3db coupler is

$$M_c = 1/\sqrt{2} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}$$

For entire mach-zehnder interferometer structure the relation between input field intensities and output field intensities is given by:

$$\begin{pmatrix} E_{O1} \\ E_{O2}\ E_{i2} \end{pmatrix} = \begin{pmatrix} M_C\ M_{\Delta\Phi}\ M_C \end{pmatrix} \begin{pmatrix} E_{i1} \end{pmatrix}$$

$$\Delta L = C/2\ n_{eff} \Delta f$$

where Δf is the frequency difference of two wavelengths

$$p_{out} = p_{in}/2 \quad 1+v\left(\cos\Delta\Phi\right)$$

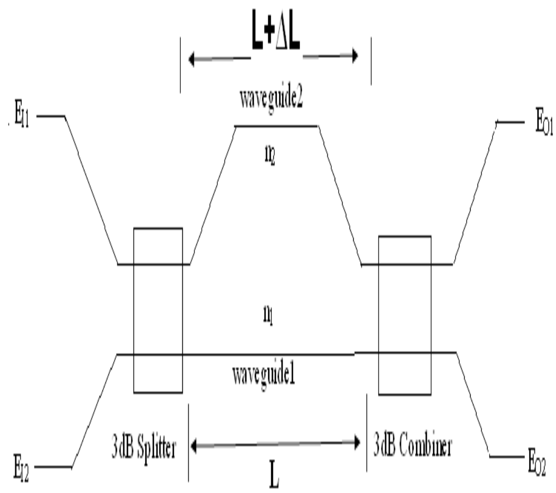

Figure 3.1:2×2 Mach-Zehnder Interferometer

2.1.2 Domain Equation:

This model shows how the Electromagnetic Waves, Beam Envelopes interface can be combined with the Electrostatics interface to perform simulations of theproperties of an optical waveguide modulator

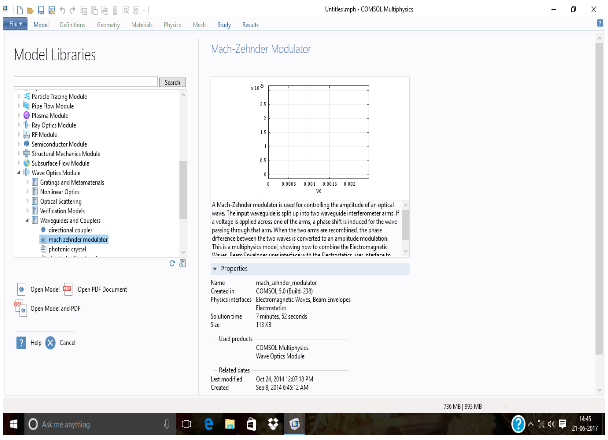

Figure 2.1The COMSOL Multiphysics Model Navigator

To illustrate the uses of these application modes and other ways to put COMSOL Multiphysics to work, we include prewritten ready-to-run models of familiar and interesting problems in the Model Library. This consists of two elements: model files installed with COMSOL Multiphysics and a dedicated manual (the COMSOL Multiphysics Model Library). Simply load one of them into the Model Navigator to view the models settings and the solution. As noted earlier, each model includes extensive documentation complete with technical background, a discussion of the results, and step-by-step descriptions of how to set up, solve, and postprocess the model.

Next comes the solution stage. Here COMSOL Multiphysics comes with a suite of solvers, all developed by leading experts, for stationary, eigenvalue, and time-dependent problems. For solving linear systems, the software features both direct and iterative solvers. A range of preconditions are available for the iterative solvers. COMSOL Multiphysics sets up solver defaults appropriate for the chosen application mode and automatically detects linearity and symmetry in the model. A segregated solver provides efficient solution schemes for large Multiphysics models, turbulence modeling, and other challenging applications.

» Surface plots
» Slice plots
» Iso surfaces
» Contour plots
» Deformed shape plots
» Arrow plots
» Streamline plots and particle tracing
» Cross-sectional plots

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3. CONCULSION:

A Mach-Zehnder Interferometer can be used to precisely vary and measure very small phase shifts in a beam of coherent light. We are using it to find the refractive index of biological sample. The phase variations caused by a liquid sample can be measured by Mach-Zehnder Interferometer. The Mach-Zehnder Interferometer, as a high sensitive refractive index-sensor can be used to detect refractive index in the surrounding medium. Due to the high sensitivity towards refractive index, the Mach-Zehnder Interferometer is attracted towards chemical, biological and biochemical sensing applications.

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