Title

Analysis of the Effective Refractive Index of Silicon Waveguides Through the Constructive and Destructive Interference in a Mach–Zehnder Interferometer

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Analyzing the Effective Refractive Index of Silicon Waveguides Using a Mach–Zehnder Interferometer

1. Introduction

In a Mach-Zehnder interferometer, the effective refractive index can be altered by tapering one of the arms of the interferometer. Thus, the delta of the effective refractive indices of two waveguides with different widths can be found. To do this, a Mach-Zehnder interferometer composed of a Y-branch splitter that splits light evenly into the two arms and a multimode interference coupler that recombines the light into the outputs was used. By measuring the transmission, the delta of the effective refractive indices could be calculated.

2. Background

The experimental method revolves around the use of a Mach-Zehnder interferometer. These interferometers involve a beam splitter that splits incoming light from the input port into two different paths before reconverging to the two outputs. The method described in the paper utilized a Mach-Zehnder interferometer composed of a 50/50 Y-branch splitter and a multimode interference coupler, as depicted in Fig. 1. The multimode interference coupler recombined the light into three ports - all light is coupled to the middle port if the two signals are in phase, and is split evenly between the top and bottom ports if the two signals are π out of phase. The phase difference can be altered by varying the optical path length differences between the two paths; this is done either by changing the physical distance or the refractive medium. The phase difference accumulated by traveling over a distance L is given in (1), where λ is the wavelength and n_{eff} is the effective refractive index of the waveguide.

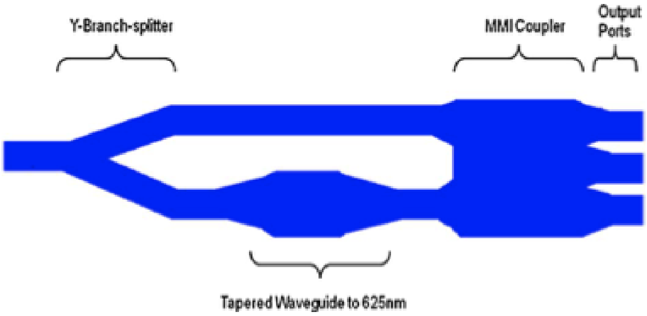

Fig. 1 The Mach-Zehnder interferometer with a tapered waveguide

$$\phi(L) = \frac{2\pi}{\lambda} \int_0^L n_{eff}(x)\, dx \tag{1}$$

To analyze the waveguide, the effective index method was used as an approximation. This method is based on the assumption that the waveguide is an asymmetric case. First, a solution for the TE (or TM) mode is found by taking a 2D cross section view of the waveguide and the width is assumed to be infinitely wide. Then, an effective refractive index is calculated and used instead of the refractive index when assuming a 2D top view of the structure. This allows for the solution of the TM (or TE) mode to be found, and allows for the final effective refractive index of the 3D waveguide to be found. The mode condition for the modes is given by (2); this condition is satisfied by discrete values of the propagation constant β. After obtaining the values of β from the TE mode, each β is used to solve for the effective refractive index using (2). This effective index is then used to solve for the solutions of the TM mode, which provides discrete solutions β of the mode condition. These conditions are then used to solve for the effective refractive index of the 3D waveguide.

$$\tan(ht) = \frac{p+q}{h(1-\frac{pq}{h^2})}. \qquad q = \sqrt{\beta^2 - k_0^2 n_1^2}, \quad p = \sqrt{\beta^2 - k_0^2 n_3^2}, \quad h = \sqrt{k_0^2 n_2^2 - \beta^2}$$
$$k_0 = 2\pi/\lambda_0, \quad \beta = k_0 n_{eff} \tag{2}$$

3. Experiment Summary

The method discussed in the paper utilized a Mach-Zehnder interferometer that varied the effective refractive index of one arm by tapering it from 525 nm to 625 nm and back to 525 nm. The transmission of the middle port was measured, as shown in Fig. 2 - the theoretical transmission of the light coupled into the middle output port is a black line, the measured results are blue dots, and the Lumerical FDTD is a dashed red line. The Lumerical FDTD shows that around 5% of input light to the multimode interference coupler was lost due to being incorrectly coupled. The delta effective refractive index is given by (3), where T is the middle output port's measured transmission, λ is the wavelength, k is the number of 2π phase differences introduced in the wider waveguide when traveling a distance L. Using (3) gives an average measured value of 0.1031 for the delta effective refractive index, and a standard deviation of 0.0474. The average theoretical value of the delta effective refractive index was 0.1238. Most sources of error could be attributed to fabrication imperfections. As shown by the results, the theoretical and measured values of the delta effective refractive index were very correlated.

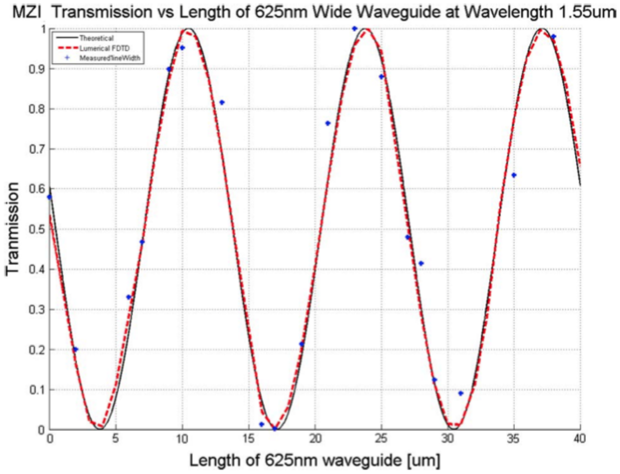

Fig. 2

$$\Delta n_{eff} = \frac{\lambda}{2\pi * L} * \left[\cos^{-1}(2 * T - 1) + 2\pi * k\right], \qquad k = 0, 1, 2, \ldots, \infty \tag{3}$$

References

Dattner, Y.; Yadid-Pecht, O. (2011). Analysis of the Effective Refractive Index of Silicon Waveguides Through the Constructive and Destructive Interference in a Mach–Zehnder Interferometer. , 3(6), 1123–1132. doi:10.1109/jphot.2011.2171678