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Method for measuring waveguide propagation losses by means of a Mach–Zehnder Interferometer structure

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ABSTRACT

In this paper, a method for measuring waveguide propagation losses by means of a Mach–Zehnder Interferometer (MZI) structure is reported. The method, based on the analysis of the transmission spectra of asymmetric MZIs, enables the propagation losses of the optical waveguides to be calculated without the requirement of identical coupling conditions for each measurement. In addition, the power imbalance of the branching structure in the MZI can also be obtained. Our theoretical analysis is supported by experimental measurements.

1. Introduction

On-chip integration of discrete photonic components is a long-standing goal of integrated optics. Silicon-on-insulator (SOI) turned out to be a suitable platform to reach impressive levels of integration [1]. Indeed, the combination of well-controlled complementary oxide-metal semiconductor (CMOS) fabrication processes and high refractive index contrast between silicon ($n = 3.5$) and silica (1.45) enables the realization of integrated waveguides with submicron cross-sections featuring single mode propagation at telecommunication wavelengths.

The extreme light confinement in SOI optical waveguides paved the way toward the realization of ultra-dense photonic integrated circuits on a single silicon chip but may result in significantly enhanced propagation losses due to the increased interaction of the optical mode with sidewall roughness [2]. Because high losses are prohibited for the majority of applications, smoothing techniques have been successfully developed to reduce light scattering [3]. Nonetheless, the propagation losses of any given integrated silicon device are to be systematically characterized.

Numerous methods have been developed to estimate this critical parameter. Some of them, such as the two-prism and three-prism methods [4–6], consist in measuring the light scattered above the waveguide under study. The advantage of these techniques is that no constant coupling conditions are required. However, the quality of the wafer surface is crucial, which limits therefore the measurement accuracy. Other methods are based on measuring the absorbed optical power [7], but in this case, the coupling efficiency is critical. Moreover, the well-known cut-back method, which is based on a comparison of the transmission through waveguides of different lengths, has been widely employed owing to its ease of use. However, it requires identical coupling conditions, which is difficult to achieve in practice [8,9]. As an alternative, the Fabry–Perot method and its modified versions have been proposed to estimate the propagation losses independently of the coupling losses. However, this method is based on the use of reflective facets, which are avoided in practical devices where high efficiency coupling techniques are precisely used to reduce the facet reflections and improve coupling [10–12].

In this paper, we propose and demonstrate experimentally a method that is independent of the fiber-waveguide coupling losses, so that identical coupling conditions for each measurement are not required. The method is based on the analysis of the transmission spectra of asymmetric MZIs, which enables the calculation of the propagation losses as well as the power imbalance of the branching structure of the MZI.

2. Theory and optical structure analysis

The passive optical component is an asymmetric MZI consisting of two identical branching elements, which in this case are conventional Y-junctions and arms having different lengths (with ΔL of length difference). As shown in Fig. 1, light is divided at the input and then recombined at the output through the branching elements. The splitter and combiner components may either be Y-junctions or multimode interference couplers (MMI). The optical waveguides have a width of 500 nm to ensure single mode transmission.

Ideally, the branching elements should split and recombine the input power equally in both arms. However, this is not always true

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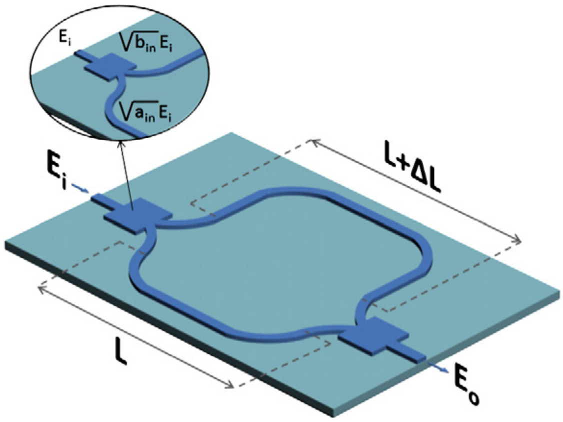

Fig. 1. Schematic view of the MZI structure. Splitter and combiner portions are represented by a generic box.

due to fabrication process deviations and may therefore have a significant impact on the component performance, depending on the application [13–15]. Therefore, in our analysis, we initially consider the most general case of having branching elements with different performances at the input and output of the MZI structure. At the branching element acting as a power splitter, i.e. located at the MZI input, the amount of power coupled to the shorter arm is denoted a_{in} while the amount of power coupled to the longer arm is denoted b_{in}. In a similar way, we can denote a_{out} and b_{out}as the power coupling coefficients that govern the output branching element, which acts as a power combiner.

Starting from of the transfer function of a MZI and assuming the same propagation losses for both arms, we can obtain the maximum electrical field at the MZI output as:

$$E_{max} = E_i\left[\sqrt{a_{in}}\sqrt{a_{out}}e^{-\alpha L} + \sqrt{b_{in}}\sqrt{b_{out}}e^{-\alpha(L+\Delta L)}\right] \tag{1}$$

where E_i is the input electric field including coupling losses, α(Np/cm) is the propagation losses in the MZI arms, L(cm) is the length of the shorter MZI arm and ΔL(cm) is the length difference between the MZI arms.

To obtain the expression for the minimum electric field, there will be an uncertainty because we do not know a priori if the output power from the longer arm is lower or higher than that from the shorter arm as it will depend on the branching elements, propagation losses and length difference between the MZI arms. Therefore, for the sake of simplicity, we can define the minimum electric field at the MZI output as:

$$E_{min} = E_i\left[\sqrt{a_{in}}\sqrt{a_{out}}e^{-\alpha L} - \sqrt{b_{in}}\sqrt{b_{out}}e^{-\alpha(L+\Delta L)}\right]. \tag{2}$$

It should be pointed out that this value may be either positive or negative. Combining Eqs. (1) and (2), we can obtain the following linear equation:

$$E(dB) = \Delta L(\text{cm}).\alpha(dB/\text{cm}) + R(dB) \tag{3}$$

where

$$E(dB) = 20\log_{10}\left(\frac{E_{max}+E_{min}}{E_{max}-E_{min}}\right) \tag{4}$$

$$R(dB) = \begin{cases} 20\log_{10}\left(\dfrac{\sqrt{a_{in}}\sqrt{a_{out}}}{\sqrt{b_{in}}\sqrt{b_{out}}}\right), & E_{min} > 0 \\ 20\log_{10}\left(\dfrac{\sqrt{b_{in}}\sqrt{b_{out}}}{\sqrt{a_{in}}\sqrt{a_{out}}}\right), & E_{min} < 0 \end{cases} \tag{5}$$

and R(dB) is denoted as the branching ratio. As can be noticed in Eq. (5), the exact expression of the branching ratio will depend on the sign of the minimum electric field obtained from Eq. (2). However, in both cases, the branching ratio value derived from Eq. (3) will indicate the degree of asymmetry of the branching elements. For perfectly symmetric branching elements, R(dB) = 0 while as the asymmetry in the branching elements increases R(dB) will give rise to values greater or lower than zero. Hence, considering a set of MZIs with different optical length differences (ΔL), we can represent the single parameter E(dB) as a function of ΔL for each MZI. Then, in a similar way than for the cut-back method, we linearly interpolate through these points to finally estimate the propagation losses α (dB/cm) of the MZI as the slope of the interpolated line. In addition, the intersection with the Y-axis (ΔL = 0) of the interpolated line will give the branching ratio.

The estimation of the propagation losses and the branching ratio will be independent of the coupling loss, which is demonstrated by the fact that E_i is not present in Eqs. (3)–(5). Furthermore, it should be pointed out that if the branching ratio is known, for instance from previous measurements, then only one MZI structure will be required to estimate the propagation losses, which will be easily derived just by looking at the maxima and minima of the interference transmission spectrum and applying Eq. (3).

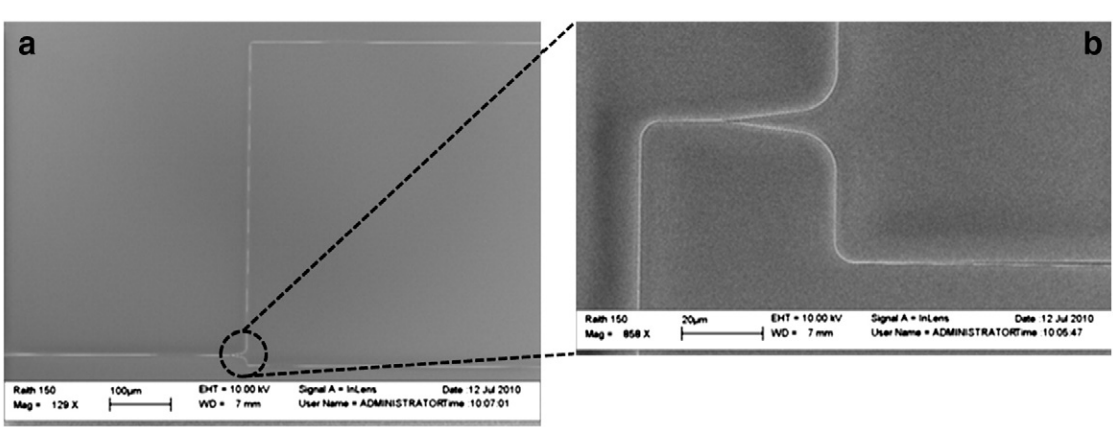

Fig. 2. Scanning electron microscope (SEM) picture of fabricated structures: (a) MZI, (b) Y-junction detail.