Accurate dispersion characterization in nanophotonic integrated waveguides

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***Abstract*—We report a method for characterizing chromatic dispersion consisting on a heterodyne fiber-based Mach-Zehnder interferometer which is immune to thermal fluctuations of fringes. The method is ideally suited to integrated waveguides, as it allows measuring dispersion and its slope versus wavelength even in short waveguides with considerable loss. We report dispersion measurements of different silicon waveguide geometries together with theoretical simulations which show good agreement with the experimental results.**

Keywords-integrated optics; silicon photonics; dispersion

I. INTRODUCTION

Transporting and processing high bitrate signals require a precise management of chromatic dispersion. Nonlinear effects are also very sensitive to, not only dispersion, but its exact dependence with wavelength, i.e. its higher order derivatives. Most of the dispersion characterization techniques were originally conceived for optical fibers, where propagation distance can be made very long in order to provide large delays. Examples of these are techniques like time-of-flight [1] or phase-shift methods [2]. A short waveguide usually is a few millimeters long, so more precise interferometric techniques are needed like the ones reported in [3-5]. These techniques employ a Mach-Zehnder or Michaelson interferometer; however, in fiber-based interferometers thermal fluctuations in each branch can cause high instability of fringe positions. If signals are low due to high insertion loss of the system, a spectrum can take several seconds or minutes, so the fringe instability can give rise to very noisy phase measurements, which can prevent an accurate characterization. In this work, we show how to compensate for thermal fluctuations using a reference counter-propagating laser beam, and we measure the dispersion of different waveguide geometries together with theoretical calculations.

II. TECHNIQUE

Fig. 1 shows the measurement apparatus. It is a fiber-based Mach-Zehnder interferometer, where one of the branches has an optical delay line (ODL), and the other has the sample. Acoustooptic modulators are also present in both branches, and they are tuned to frequencies differing 40kHz for heterodyne phase detection through a lock-in amplifier. The lock-in amplifier is referenced to the beatings produced by a counter-propagating beam at a fixed wavelength. Therefore, when sweeping the wavelength of the tunable laser, the thermal fluctuations of the optical path equally affect both beams, thus compensating the fringe instability.

To compensate for the response of the system, two measurements with different lengths are necessary, the shortest one to be used as a reference. The purpose of the ODL is to maintain the interferometer balanced in both sweeps, so the linear dependence of the phase versus frequency is removed. As the path variations in the ODL are in air, the phase difference between both measurements is given by:

$$\Delta\phi_{sample}(\Delta\omega) - \Delta\phi_{air}(\Delta\omega) = \left(L_s\beta_1 - \frac{L_a}{c}\right)\Delta\omega + L_s\left(\frac{1}{2}\beta_2\Delta\omega^2 + \frac{1}{6}\beta_3\Delta\omega^3\right) \quad (1)$$

where the ODL extra path is L_a and the device length is L_s, both lengths with respect to the reference measurement. β_i is the ith derivative of the wavenumber k versus frequency ω. The interferometer is balanced when the first term in $\Delta\omega$ is zero, which provides the value of the group index. And the other terms in $\Delta\omega^2$ and $\Delta\omega^3$ are obtained from a polynomial fit.

III. EXPERIMENT AND RESULTS

Measured samples are silicon channel waveguides embedded in silica, as shown in Fig. 2(a)-(b), which have 2μm oxide buffer, 214.7nm height and 25mm long. Sample A corresponds to a TE polarization channel waveguide with 430nm width. Sample B, used as TM polarization channel waveguide, has 487.2nm width. The sidewall angle introduced in the manufacturing process is 8° and 6° for Sample A and Sample B respectively. Total insertion losses were around 24dB for TE and 15dB for TM.

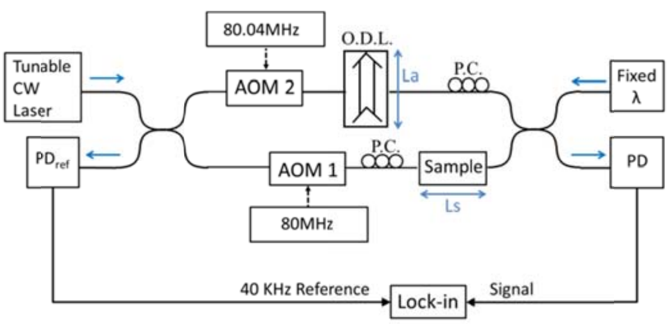

Figure 1. Experimental setup. PC: polarization controller, PD: Photo-detector, AOM: Acousto-optic modulator, ODL: Optical delay line.

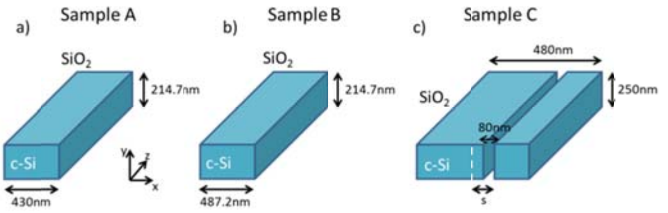

Figure 2. (a) TE polarization, (b) TM polarization, (c) vertical asymmetric slot. Waveguide parameters were extracted from SEM micrographs and were fine-tuned within the measurement error range to optimize the fitting.

Sample C is a 50% asymmetric slot waveguide which has a vertical silica slot between two silicon layers. In asymmetric slot waveguides, the slot location is different than the geometrical center of the waveguide. We define the asymmetry degree as $2s/w$, where s is the distance from the center of the waveguide to the center of the slot, in absolute value, and $w/2$ is half of the total width of the waveguide, see Fig. 2(c). The waveguide parameters are: 14mm long, 250nm height, 80nm slot width, 480nm total width and 5.5° sidewall angle. Total insertion losses were 54dB.

Fig. 3 shows the phase experimental measurement and its polynomial fit. In Fig. 4 we show the dispersion profiles obtained from the fit for each of the three different samples, where numerical simulations performed by using commercial software based on finite element method are also presented for comparison. It can be seen that dispersion values and their slopes reasonably agree with the calculations. Group indices obtained from the ODL are 4.36, 3.21 and 4.17 for Samples A, B and C respectively, while calculated values are 4.35, 3.46 and 4.15, showing a good agreement too.

IV. CONCLUSIONS

A novel method for characterization of dispersion, its dependence with wavelength, and group index, which is immune to thermal fluctuations of the interferometer has been reported. With this method, we have performed an accurate dispersion characterization of conventional silicon strip waveguides for both TE and TM polarizations and for a vertical slot waveguide. Experimental results show a close agreement with theoretical results obtained from simulation.

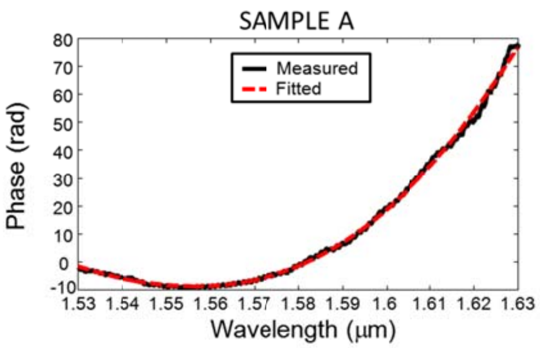

Figure 3. Phase evolution for TE polarization strip waveguide.

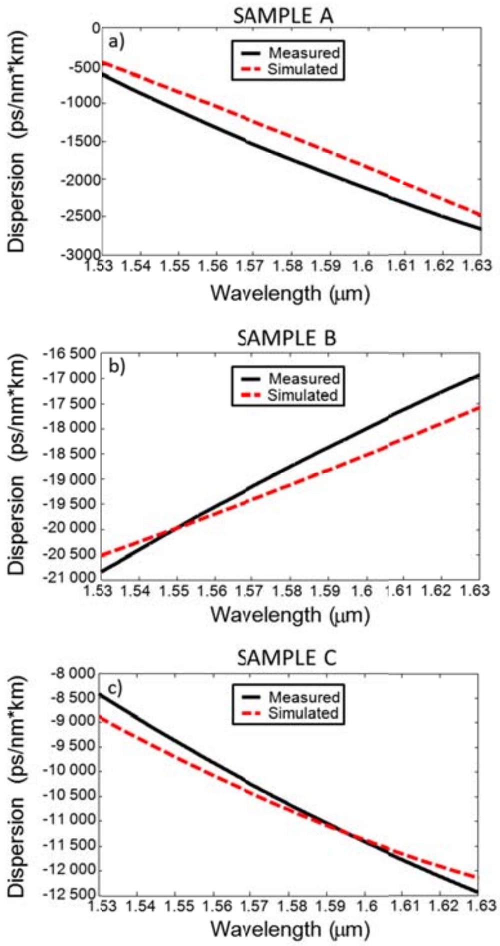

Figure 4. Chromatic dispersion profiles for (a) TE polarization, (b) TM polarization, (c) vertical asymmetric slot.

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