Real-Time Phase Trimming of Mach-Zehnder Interferometers by Femtosecond Laser Annealing of Germanium Implanted Waveguides

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***Abstract*—We demonstrate a real-time trimming technique, enabling accurate and permanent correction of typical fabrication based phase errors of integrated Mach-Zehnder Interferometers (MZIs). The output signal can be monitored during entire annealing process.**

***Keywords*—Real Time Trimming, Mach-Zehnder Interferometer, Femtosecond Laser Annealing**

I. INTRODUCTION

Silicon photonics is one of the most attractive technologies for realising a low cost solution for future high speed interconnections. The application of photonic integrated circuits (PICs) has attracted great interest from both the academic community and industry. Huge resources and efforts have been put into enhancing the performance of silicon photonics components. The Mach-Zehnder Interferometer (MZI) is one of the most widely used components among them. For most applications, the MZI needs to be working at a particular operating point, which requires accurately controlling the phase difference between the two arms. As an example, a symmetrical MZI modulator needs to be operated at the quadrature point for optimum performance [1]. However, due to the errors associated with the fabrication process and wafer variable properties, an active thermal or electrical tuning is normally required during MZI's operation to correct its phase difference, which brings substantial power consumption and control complexity. Meanwhile, many other correction methods have been investigated. For example, electron beam induced compaction and strain to the oxide cladding have been proposed to trim the peak resonance of silicon ring resonators [2]. However, small variation of refractive index in oxidation layers limits the tuning range of the resonance peak.

In our previous work, rapid thermal annealing (RTA) and a continuous wave (CW) laser were used to anneal a section of Ge implanted waveguide to trim the operating point of MZIs or ring resonators [3, 4]. The index change induced by the lattice state change of silicon is over one order more effective than the previous trimming techniques [2]. However, the annealing processes and device testing in the previous work were carried out in two separated systems.

In this paper, we adopt a new experimental set-up to realize real-time measurement of the MZI devices during laser annealing. A feed-back control was implemented for the first time in order to improve the trimming accuracy. The implementation makes use of an ultrafast laser system previously used in the spatial mapping of photonic devices (see Fig. 1) [5]. In our current work, the femtosecond pump laser in the UV range is used to anneal the Ge implantation section in the MZI arm. A pulsed probe laser and photodiode or spectrometer is used for real-time monitoring of the output of the MZI. Once the ideal operating point of the MZI is achieved during the annealing process, the pump laser can be turned off immediately.

II. DEVICE DESIGN AND LASER ANNEALING

The device design is illustrated in Fig.2. The MZI was fabricated using Silicon On Insulator (SOI) wafers with a 220nm top silicon layer and 2µm buried oxide. All waveguides for the MZI arms are 500nm wide. 2×2 multimode interference (MMI) couplers are used as the optical splitter and combiner. The MMI coupler is 44.8 µm long and 6 µm wide. To enhance optical transmission, a short taper is used between MMIs and waveguides. The devices were formed by a 120nm dry etching process. Light was coupled between fibers and waveguides through grating couplers. Only the TE mode was coupled to waveguides for characterization. The devices are measured at wavelengths around 1550 nm.

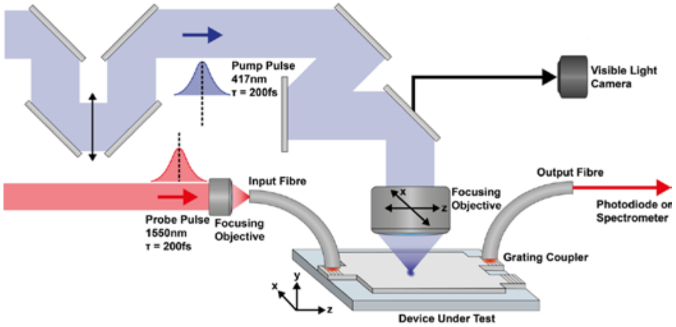

Fig. 1. Femtosecond laser real-time trimming setup.

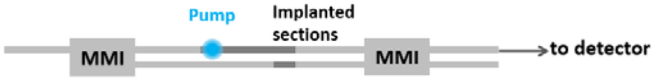

Fig. 2. Schematic illustration of MZI with Ge implanted waveguide in both arms and the real-time annealing process using a scanning laser.

The scheme of fig.2 shows that there is a Ge implanted area in both MZI arms. A longer one (7 µm long) was designed to be partly annealed and controlling the phase. A shorter one (2 µm long) was used to balance the Si/amorphous Si transition loss of both arms. After fabrication of gratings and devices, a 20 nm silicon dioxide layer was deposited as top protective layer. Then an e-beam resist layer was deposited as mask layer for the Ge implantation. According to our previous results [6], over 80% lattice disorder in silicon would give a refractive index change of 0.5. Ge implantation was performed with energy of 130KeV and a dose of 1×10^{15} ions/cm^2.

A 417 nm, 200 fs laser with power up to 10 mW was used to anneal the implanted waveguide. The laser beam was focused onto the sample using a 100x focusing objective, producing a ~900 nm diameter spot. The scanning speed can be slowed down to 0.1 μm/s. A Charge-Coupled Device (CCD) camera is used for imaging. For each MZI sample, we can record real-time transmission data or wavelength spectra as the annealed length is gradually increased. The power of the femtosecond laser was precisely controlled to achieve the desired annealing effect [7]. Fig.3 shows that annealing starts at a threshold of around 6 mW.

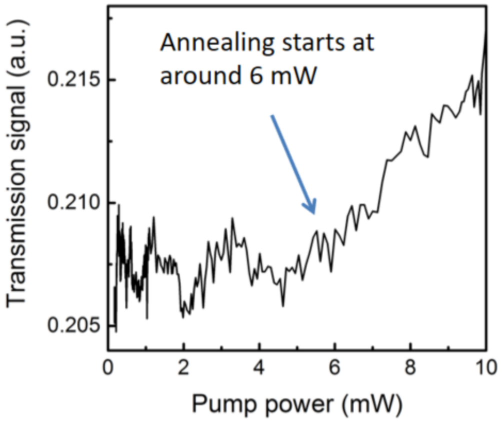

Fig. 3. Dependence of annealing on pump intensity.

III. EXPERIMENTAL RESULTS

Results for a typical MZI sample are shown in Fig.4a (first annealing scan) and Fig.4b (repeat scan). For each testing cycle, we gradually scanned the pump laser spot along the whole length of the longer implantation section. Different annealed lengths led to varying phase difference between the two arms. The starting position of the laser spot was aligned visually with the alignment marks made during fabrication, marking the end of the implanted region. The output transmission was record by a photodiode. In the first annealing scan (Fig. 4a), the output transmission decreased as the pump laser spot passed along the implanted section. In the repeat scan (Fig. 4b), the transmission had no obvious changes, which meant that this waveguide had been fully annealed during the first scanning. The small difference between final transmission of first scan and initial transmission of the second scan was caused by drift of the laser source and coupling changes.

As shown in Fig.4, a typical output transmission curve was successfully tuned by the position of the scanning laser. The output did not change further after removing the pump laser. The minimum scanning step for the pump laser spot is 10 nm and we can achieve a high phase trimming accuracy with this level of spatial resolution. With this technique, we can fine-tune each device to maximize the performance.

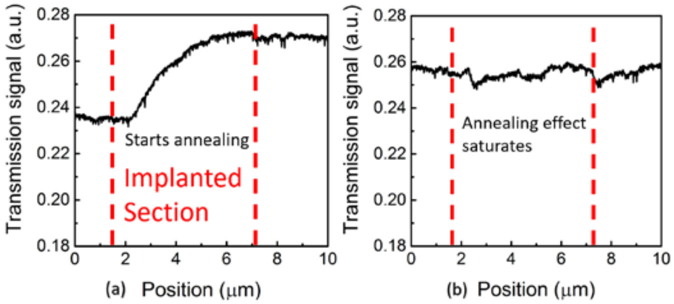

Fig. 4. Real-time measured results of MZI when pump laser scanning the implanted waveguide. (a) First scan (b) Second scan

IV. CONCLUSION

We have demonstrated a practical and highly accurate post-fabrication trimming technique for silicon integrated MZI devices, which have a Ge implantation section in the silicon waveguide that increases the refractive index. Using a femtosecond second laser we can partly anneal the amorphous silicon back into the crystalline state. The optical phase difference between both arms of the MZI can be precisely controlled by a real-time feed-back system. With a minimum 10 nm step of laser spot, we can achieve a high phase trimming accuracy.

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