Ultrahigh-sensitivity On-chip Power Monitor using a Resistive Microheater in a Silicon Waveguide

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***Abstract*—A doped-silicon microheater is routinely used to thermally tune the optical devices. We demonstrate that such a microheater assisted with an external lock-in amplifier can also work as a non-invasive ultra-high sensitivity optical power monitor. Waveguide optical power as low as -40 dBm is detected.**

I. INTRODUCTION

Silicon has an indirect bandgap energy of 1.12 eV, higher than the photon energy of 0.8 eV in the 1550 nm optical communication band. It makes silicon an attractive material for integrated photonic devices, but on the other hand also inhibits the realization of photodetection in this wavelength band. Several approaches have been demonstrated to overcome the intrinsic limitation by using two photon absorption (TPA), middle bandgap state absorption (MSA) or surface state absorption (SSA) effects [1-6]. The SSA effect is quite attractive for optical power monitoring, because it uses the regular silicon waveguide without extra ion implantation as required in MSA. Unlike the nonlinear TPA, the SSA is a linear effect and can detect optical signals at a low power level. Unfortunately, the SSA is quite weak and the induced free-carrier concentration change is orders of magnitude lower than that of a regular photodetector. In order to convert the small change into a detectable signal, a post electrical amplifier circuit is necessary.

In this work, we demonstrate optical power monitoring by applying a low-frequency sinusoidal electrical signal to a resistive microheater integrated in the silicon waveguide. The small current change across the waveguide enabled by the SSA is detected by using a high precision lock-in amplifier. The minimum detectable optical power in the waveguide can be as low as -40 dBm.

II. DEVICE STRUCTURE

Figure 1(a) shows the 3D drawing of the silicon waveguide integrated with a resistive microheater composed of two highly doped n^{++} regions (centration 1×10^{20} cm^{-3}) and a central lightly-doped n^{-} region (concentration 8×10^{16} cm^{-3}). The highly-doped regions are 0.8 µm away from the waveguide sidewalls. The n^{-} doped region works a resistor where heat will be generated when current flows through it. Such a microheater structure features a high thermal efficiency and a fast response speed, which has been used in multiple thermally tunable devices, such as filters and switches [7, 8]. A voltage of several volts is needed to generate a useful thermal phase shift. Here we use it to work as an on-chip optical power monitor. A small AC drive voltage with an amplitude of a few mV can produce high enough current without perturbing the waveguide mode. Figures 1(b) and 1(c) show the optical microscope images of a straight waveguide and an add-drop ring filter. The microheater in the straight waveguide is 1.4 mm long. The microheater in the ring resonator is divided into two parts and connected together by the metal lines with a total length of 16.8 µm.

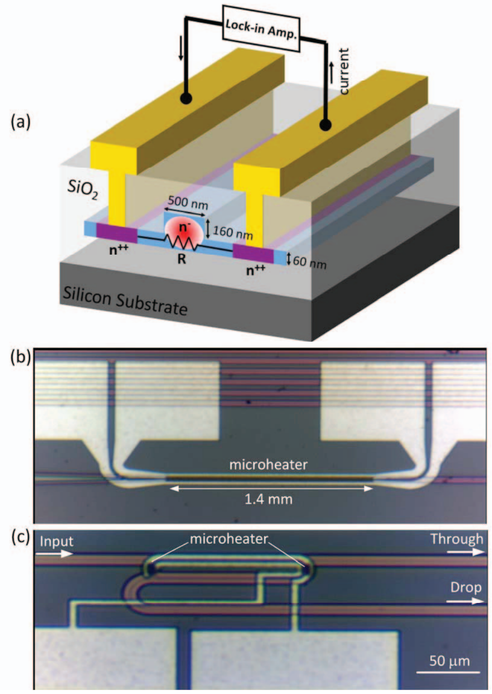

Fig. 1 (a) Schematic structure of a silicon waveguide integrated with a resistive microheater. (b) and (c) Top-view optical microscope photographs of (b) a straight waveguide and (c) an add-drop ring resonator filter.

III. EXPERIMENTS AND RESULTS

A sinusoidal electrical signal from a lock-in amplifier (Signal Recovery, Model 7280) was applied to the microheater. The current through the microheater was measured and amplified by the lock-in amplifier.

Figure 2(a) shows the measured current as a function of the electrical signal frequency at various optical power levels in the waveguide shown in Fig. 1(b). The signal voltage is only 5 mV. The measured current has a flat response to frequency between 1 kHz to 30 kHz, but dramatically decreases at the high frequency end probably due to the inductive effect of the long metal wire. The current change due to the presence of optical beam in the waveguide is significant when the optical power is high.

The magnitude of the current is dependent on the voltage as shown in Fig. 2(b). The I-V curve has a linear response as expected. The slope of the line reflects the conductance of the microheater. Higher optical power increases the conductance due to the increased free carrier concentration by SSA, thereby resulting in a larger slope.

In order to see clearly how the SSA increases the current, Figure 2(c) presents the photon-induced current change by subtracting the dark current (laser off) from the measured current. It can be seen that the optical power as low as -40 dBm can still cause a small current variation detectable by the lock-in amplifier.

Figure 2(d) presents the photon-induced current change as a function of on-chip optical power at two frequencies (200 kHz and 1.76 MHz) and two drive voltages (5 mV and 40 mV). The current change shows a sub-linear response to the optical power. The measurement at the lower frequency and the higher voltage gives the more significant current change.

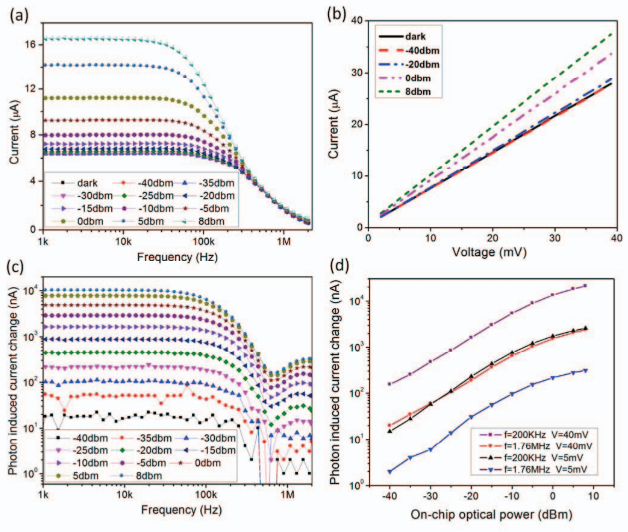

Fig. 2 Optical power monitoring of a silicon waveguide. (a) Measured current as a function of frequency at a drive voltage of 5 mV. (b) I-V curve at an electrical signal frequency of 200 kHz. (c) Photon-induced current change as a function of frequency at a drive voltage of 5 mV. (d) Photon-induced current as a function of on-chip optical power.

We also employed the technique to measure the ring resonator shown in Fig. 1(c). The drop transmission spectrum of TE polarization was first measured by using a scanning laser test system as shown by the solid blue line in Fig. 3. The quality factor is Q ≈ 20000. The lock-in amplifier was then turned on to measure the current through the microheater. The drive voltage was 50 mV and frequency 200 kHz. The optical power in the input waveguide was -4.8 dBm. The measured current change as a function of wavelength is shown by the dashed red line. At the resonance wavelengths, the optical power is greatly enhanced in the ring waveguide, and therefore the current increases sharply when approaching the resonances. We can see that the electrical signal profile matches well with the optical transmission spectrum, indicating the effectiveness of the optical power detection method in monitoring the resonances. To confirm that the small AC signal is non-invasive to the ring resonator, we compared the transmission spectra before and after applying the electrical signal. It reveals that there is no resonance wavelength shift observed under the laser scanning resolution of 0.1 pm.

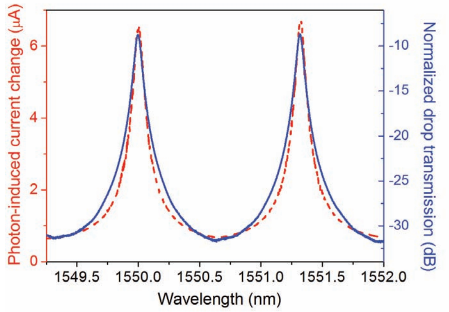

Fig. 3 Comparison of the electrical signal measured with the lock-in amplifier and the drop-port transmission spectrum of a ring resonator measured with the scanning laser.

IV. CONCLUSIONS

We have demonstrated optical power monitoring using the doped silicon-based microheater. Optical power in the waveguide as low as -40 dBm can be detected by using the lock-in amplifier. The detection is non-invasive with no perturbation to the normal operation of optical devices. Such a technique is useful in integrated silicon photonics as it reutilizes the existing microheaters already on the chip.

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