Temperature-insensitive control strategy for photonic ICs using photo-thermal plasmonic sensors

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***Abstract*—We present a novel optical sensor for light detection in photonic integrated circuits based on the photo-thermal plasmonic effect. We demonstrate its effectiveness in locking a Micro-Ring Resonator at resonance, using a control technique which is insensitive to crosstalk from thermal actuator to photo-thermal sensor.**

***Keywords*—plasmonics, integrated photonics, optical sensor, closed-loop control, thermal crosstalk compensation**

I. Introduction

Recent advancements in the field of Photonic Integrated Circuits (PICs) have pushed their use in numerous applications, from high-speed modulators [1] to programmable optical filters [2], optical neural networks [3] and optical processors [4]. The growth of these circuits in terms of complexity and size calls for strategies to measure the optical power of each integrated device, in order to set and monitor their working point and act in real-time to compensate for possible fluctuations due to thermal drifts and aging. The measurement of optical power should be performed while introducing minimal losses, thus rendering standard photodetectors unpractical as they would require to tap the waveguide to extract non-negligible amounts of power.

The photo-thermal plasmonic sensor is proposed [5] as a viable solution to these aspects, allowing for ubiquitous positioning and technology independence thanks to its technological simplicity. The sensor consists of a metal strip placed in contact with the waveguide core, which exploits the propagation of Surface Plasmon Polaritons (SPPs) at the metal-dielectric interface. Here, the sensor has been characterized and used in a closed-loop control of a Micro-Ring Resonator (MRR), in order to lock it at resonance in presence of external perturbations. The dithering-based control technique employed proved successful even when using thermal actuators and photo-thermal sensors, showing no crosstalk between the two.

II. Photo-thermal Plasmonic Sensors

The cross-section and top-view photograph of the realized photo-thermal plasmonic sensor are shown in Fig.1a. A gold plate is placed on top of a standard silicon waveguide through an intermediate Al_2O_3 (alumina) layer, forming a hybrid plasmonic configuration. When the optical field reaches the sensor, it gets confined in the alumina layer, exciting two SPP modes at the metal-dielectric interface [5]. The SPP modes propagate with different phase velocities and thus interfere while traveling along the sensor. With a careful choice of the sensor length L, the interference is constructive at the end of the electrode and the optical field couples back into the silicon waveguide introducing minimal losses.

When confined at the gold interface, the plasmonic modes scatter, heating up the metal and changing its resistance according to the formula:

$$R(T) = R_0\left[1 + \alpha\left(T - T_0\right)\right] \tag{1}$$

where $R_0 = 40\,\Omega$ is the resistance at room temperature T_0 and $\alpha = 0.002\,\mathrm{K}^{-1}$ is the gold temperature coefficient. Using the four-probe lock-in scheme in Fig.1b the value of this resistance is extracted by forcing a stimulus current I_{stim} and measuring the voltage across the sensor with an Instrumentation Amplifier (INA).

The sensor has been characterized, and the results are shown in Fig.1c. Using different current amplitudes I_{stim} and sweeping the optical power, the sensor exhibits excellent linearity over the measured range. Indeed, using (1) and Ohm's law it is possible to derive:

$$\Delta V_{sens} = I_{stim} \cdot \Delta R = I_{stim} \cdot R_0 \cdot \alpha \cdot \Delta T|_{P_{OPT}} \tag{2}$$

where $\Delta T|_{P_{OPT}}$ is the light-induced temperature variation and is proportional to the optical power in the waveguide. Using a stimulus current of $100\,\mu\mathrm{A}$, the measurements show a sensitivity of $30\,\mu\mathrm{A/mW}$, which improves by using a larger current. The detector reaches a minimum detected power of $30\,\mathrm{dBm}$: the lower bound is ultimately set by the readout electronic noise, and can be further improved using a custom optimized setup.

III. Control of a Micro-Ring Resonator

The sensor has been integrated on the through port of a MRR and used with a thermal actuator in a closed-loop control system (Fig.1d), in order to stabilize the ring in presence of external perturbations. The control strategy is based on the dithering technique [6]: by adding a small oscillation v_{dith} to the voltage driving the actuator, the working point of the ring is modulated, producing at the output an oscillation whose amplitude is proportional to the first derivative of the ring

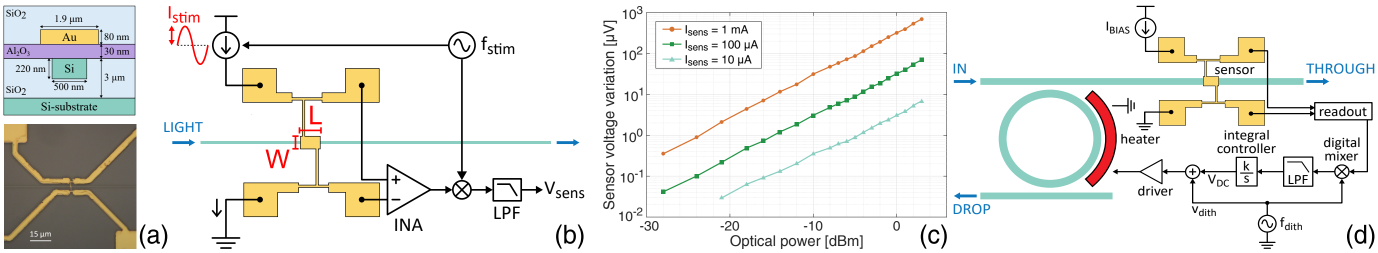

Fig. 1. (a) Cross-section (top) and top-view photograph (bottom) of the sensor. (b) Schematic of the four-probe lock-in detection scheme. (c) Sensor sensitivity at different stimulus currents. (d) Schematic of the dithering-based control loop on a Micro-Ring Resonator (MRR).

transmittance. The readout stage extracts the amplitude of the oscillation and feeds it to an integral controller, which updates the actuator DC voltage until the derivative is zeroed, effectively locking the ring at resonance.

The control system has been tested perturbing the MRR with incremental wavelength steps of $100\,\mathrm{pm}$. Fig.2 shows the measured optical output power and heater voltage, proving the effectiveness of the loop in locking the ring at resonance with a response time of about $10\,\mathrm{ms}$, fast enough to compensate for thermal drifts.

IV. Compensation of Thermal Crosstalk

By using a thermal actuator and a photo-thermal plasmonic sensor, an issue comes from possible crosstalks between the two, which would result in the ring locking in the wrong working point. Indeed, as shown in Fig.3, when no light is present and the heater power is swept from 0 to $60\,\mathrm{mW}$, the sensor detects the power variation, with an error that reaches 0.4%. This error corresponds to about $10\,\mu\mathrm{V}$ at $I_{stim} = 100\,\mu\mathrm{A}$, big enough to be wrongly interpreted as an optical power of $-5\,\mathrm{dBm}$ (see Fig.1c).

However, when using the dithering technique, the sensor is readout only at the oscillation frequency f_{dith}: at that frequency, considering a sinusoidal oscillation v_{dith} superimposed to the DC voltage, the modulated heater power is:

$$P_{dith} = 2 \cdot V_{DC} \cdot v_{dith} / R_{heater} \tag{3}$$

which equals at most $500\,\mu\mathrm{W}$ when a voltage oscillation of $20\,\mathrm{mV}$ is superimposed to a $V_{DC} = 5\,\mathrm{V}$ and the heater resistance is $400\,\Omega$. This power level, although sufficient to operate the control loop, is not detected by the sensor. Therefore, the proposed control scheme is able to compensate for possible temperature fluctuations in the photonic integrated circuit while also cancelling out the effect of thermal crosstalk, enabling stable operation for photonic devices.

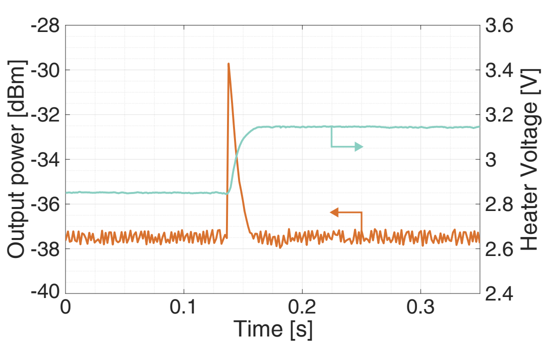

Fig. 2. Measurement of the control system response to a wavelength step of $100\,\mathrm{pm}$ applied at t=$0.13\,\mathrm{s}$. The system is able to automatically recover the resonance in about $10\,\mathrm{ms}$.

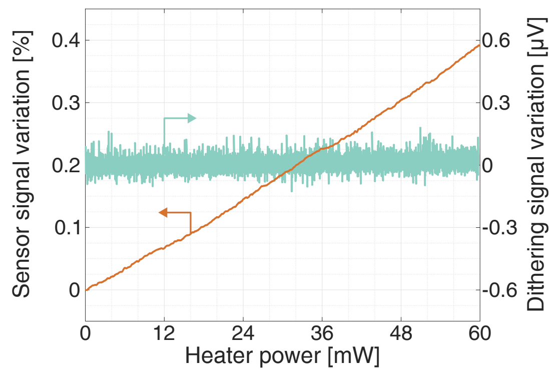

Fig. 3. Measurement of the thermal crosstalk when operating in open loop (orange) and in closed loop with the dithering technique (light blue).

Acknowledgments

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