In-line photo-thermal plasmonic detectors integrated in TiO_2 optical waveguides

(Student paper)

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We demonstrate a compact in-line surface plasmon photo-thermal detector integrated on a TiO_2 photonic platform. The detector is only 1.6 µm long and shows a sensitivity of −20 dBm with a bandwidth of more than 100 kHz and an insertion loss of 2.3 dB.
Keywords: *Photo-thermal detector, plasmonic, waveguides*

INTRODUCTION

Photonic Integrated Circuits (PICs) are evolving towards architectures with an ever-increasing scale of integration, which implement more and more complex functionalities. To develop PICs that can be reconfigured reliably, on-chip photodetectors must be integrated to locally monitor the optical power and closed-loop control systems have to be designed to set and stabilize their working point. Semiconductor photodetectors are widely employed in the near infrared-range because of their small size, fast detection speed, high detection efficiency [1] and monolithic integration on silicon and III-V photonic platforms. This family of transducers includes photodiodes [2], photoconductors [3] and sub-band-gap detectors based on surface state absorption [4]. However, these approaches cannot be deployed onto dielectric waveguide platforms, such as silicon nitride or oxide waveguides. We propose here a solution to this problem by integrating an in-line photo-thermal detector. The device consists of a metal strip placed underneath the waveguide sustaining surface plasmons polaritons (SPP). SPPs favor the absorption of optical power and from the temperature-dependent change of the metal resistivity it is possible to monitor the transmitted optical power by measuring the voltage drop across the metal [5,6,7]. Different configurations have been proposed for photo-thermal detectors such as a Wheatstone bridge [6] and the use of hybrid plasmonic waveguides [5].

In this work, we designed an in-line Surface Plasmon Detector (SPD) integrated in a TiO_2 platform that exploits the photo-thermal effect to monitor the optical power inside the waveguides. To maximize the responsivity of the device, we investigate the effect of the metal strip size in the coupling between the dielectric and plasmonic modes, the power dissipated in the metal, and the equivalent thermal resistance of the structure. We use a 3D Field Element Method multi-physics study including an optical, thermal, and electrical analysis. Experimental results show a sensitivity of −20 dBm and a bandwidth of about 100 kHz in an SPD with a length of only 1.6 µm.

DESIGN AND NUMERICAL ANALYSIS

The waveguide used for this work is realized with an air cladded 1.2 µm-wide and 370 nm-high titanium dioxide (TiO_2) core above a 2 µm-thick silicon dioxide (SiO_2) layer thermally grown of Si wafer. The SPD consists of a 30 nm-thick gold (Au) strip [see Fig. 1(a) and (b)] realized by a first step of e-beam lithography prior to the deposition of a TiO_2 layer. The layer is then structured by a second e-beam lithography combined with reactive ion etching to produce waveguides and grating input and output couplers. The waveguide and the detector are optimized to work at 1550 nm. A top view photograph of a fabricated SPD device is shown in Fig. 1(c).

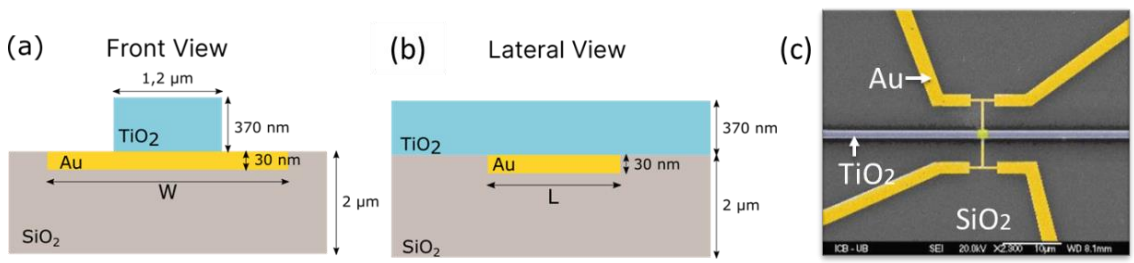

Fig. 1. Surface Plasmon Detector (SPD) geometry. (a) Front view of the SPD. The waveguide is made of TiO_2 (turquoise), the detector is Au (yellow), and the cladding is SiO_2 (tan). (b) Lateral view of the SPD. (c) Scanning electron micrograph of the fabricated device showing the sensing section underneath the waveguide and the access microscopic electrodes.

Surface plasmon modes are influenced by the thickness of the metal over which they propagate. For thick strips the evanescent component of the field penetrates more into the metal. However, the rapidly decaying SPP mode profile makes this contribution too small to dominantly affect the SPP mode propagation loss α [8]. Furthermore, if the gold is too thick, the large discontinuity of the propagation medium at the edges of the Au strip would severely increase backreflections and scattering and reduce the coupling to the detector. We find that α depends mostly on the field intensity adjacent to the Au strip, which increases for thinner strips. Thus, for sensing applications, the metal thickness should be maintained thin enough to reduce losses and increase the gold absorptance. The length of the detector L is the fundamental design parameter as it determines the amplitude of the transmitted optical wave and the gold absorbed power. For this structure, the SPD has a numerically determined fundamental SPP mode with a complex-refractive index n_{eff} = 2.096 - i0.019 which corresponds to a propagation loss of 0.67 dB/µm.

The simulated normalized transmittance P_{tx} versus the detector length is shown in Fig. 2(a). If the dielectric mode is TM polarized(orange) two independently propagating SPP modes are excited [9]. These modes propagate along the top and bottom surfaces of the metal with different speed and, depending on L, they will interfere constructively or destructively at the end of the strip. For this reason, the TM P_{tx} follows a decaying sinusoid with an oscillation period of 2.4 µm. For L = 1.1 and 3.5 µm, the SPP modes are out of phase and P_{tx} is almost zero. Instead, for L = 2.3 and 4.6 µm, the SPP modes are in-phase and P_{tx} is maximum, although not equal to P_{in} due to coupling losses and gold absorption. On the other hand, the TE mode cannot excite the SPP modes and therefore it has an almost flat P_{tx}. The small fluctuations are caused by a Fabry-Perot cavity effect. Yet as the detector length increases, this effect reduces due to the absorption of the gold. As a result, the TE transmittance flattens after L = 3 µm. The cavity effect is also present in the TM mode but the beating between the two SPP modes remains the dominant effect.

The losses efficiency η defined as the ratio between the actual power dissipated in the gold P_d and overall losses P_l gives a direct measurement of the capacity of the gold to transform all the lost power into heat. In Fig. 2(b), the simulated losses efficiency is shown, highlighting how the TM mode (orange) exhibits both the oscillations mentioned previously: the fast fluctuations (500 nm period) due to the Fabry-Perot cavity are superimposed to the wide oscillations (2.4 µm period) due to the coupling of the SPP propagating modes. For short lengths, P_l is dominated by the coupling mismatch and η is low. As the length increases the coupling losses remain constant but P_d increases and so does η. An efficiency of 42.5% is achieved for the TM mode at L = 2.3 µm and 50.4% at L = 4.7 µm, which coincide with the transmittance peaks. This is a remarkable result since there are lengths for which the transmitted optical power and gold absorptance are maximum. The low efficiency (below 55%) is caused by the coupling losses and the mismatch between the waveguide mode and the SPPs modes, and it can be significantly improved by introducing a mode adapter at the input/output sections of the plasmonic waveguide.

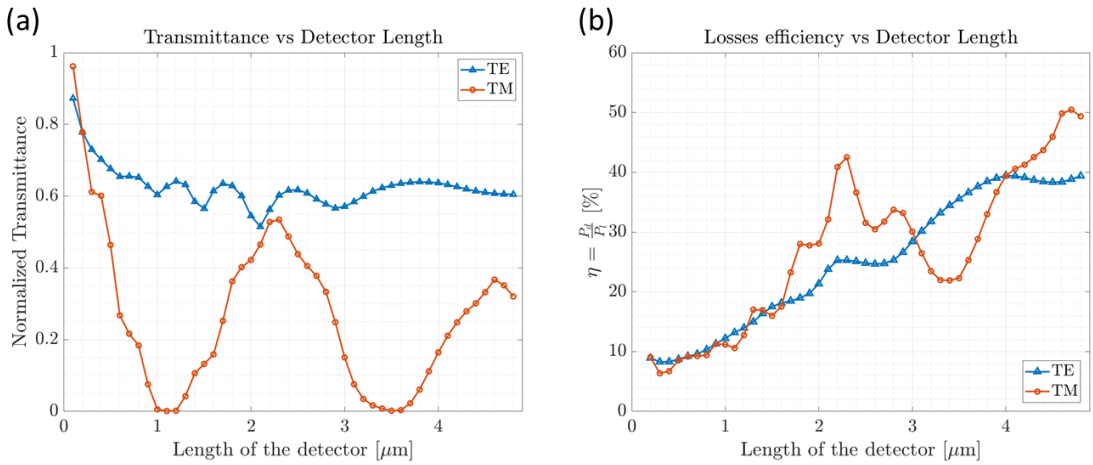

Fig. 2. (a) Normalized transmittance vs the length of the SPD. The TM excites two SPP modes that interfere constructively (L = 2.3 µm and 4.7 µm) or destructively depending on L. (b) Losses efficiency of the SPD. The maximum efficiency coincides with the maximum transmittance shown in (a).

DEVICE FABRICATION AND CHARACTERIZATION

Straight waveguides integrating a different number of cascaded detectors with the same length (L = 1.6 µm) were fabricated to assess the excess loss and the back reflections of the SPD. The TiO_2 waveguides are 1200 nm-wide, 370 nm-high and 1.5 mm-long. Light coupling into the chip was achieved by using grating couplers designed to operate on TM polarization. The metal layer of the detector has a thickness of 37 nm (3 nm Cr adhesion layer + 34 nm Au) and a width of 3 µm and it was deposited directly on top of the SiO_2 layer below the TiO_2 core of the waveguide.

By measuring the transmitted optical power, over a wavelength range from 1520 nm to 1580 nm, an insertion loss *IL* of about 2.3 (± 0.3) dB was observed, which is very close to the 2.0 dB estimated from electromagnetic simulations. To obtain the reflected power of the SPD, a circulator was added before the input fiber to collect the back reflected signal from the waveguide. A coherent optical frequency domain reflectometry (OFDR) [10] technique was employed to obtain the reflection coefficient of each SPD amounting to –17 dB.

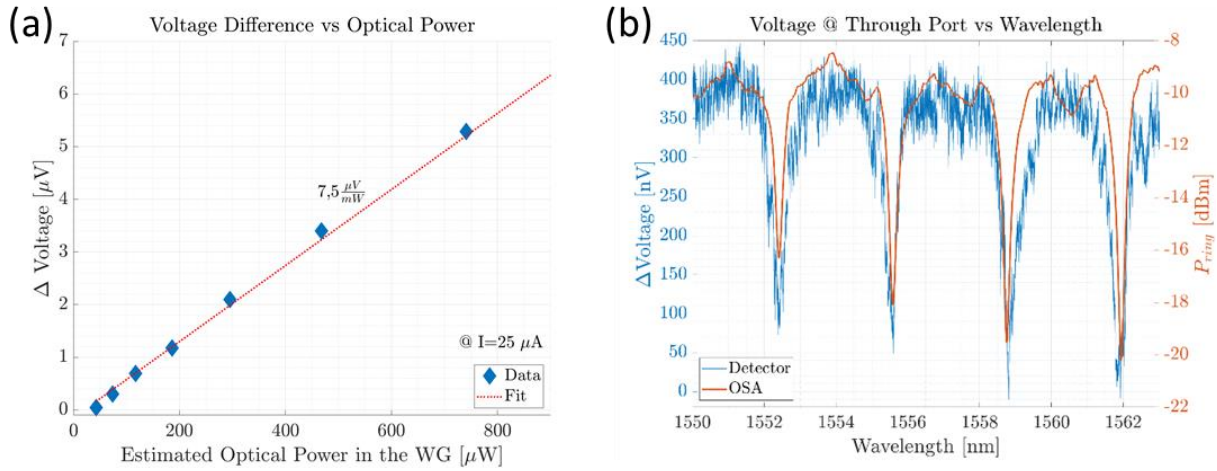

Fig. 3. (a) Measured responsivity of the SPD for I_{bias} = 25 µA. (b) Spectral response of a ring resonator acquired with the SPD.

Figure 3(a) shows the light-dependent change of the voltage drop across the gold strip of the SPD, as measured by a lock-in scheme, for increasing power in the waveguide, when a bias current I_{bias} = 25 µA is applied. The voltage is linear versus the optical power and the responsivity R_d, which is given by the slope of the linear fit (red), equals 7.5 µV/mW. The SPD can operate over a 15 dB dynamic range with a minimum detectable power of P_{in} = -20 dBm. These values can be improved by increasing the I_{bias}. The response time of the SPD was measured by modulating the input light with a square wave at 20 kHz and reading the detector voltage with an oscilloscope triggered by the modulating signal. The resulting time constant was 1.2 (± 0.07) µs, that corresponds to a bandwidth of 132 kHz.

SPDs were also integrated at the output port of a microring resonator to monitor the wavelength response of the device. An example is reported in Fig.3(b), where the blue curve is the SPD measurement, while the reference curve (in orange) is acquired with an external optical spectrum analyser. The good agreement demonstrates the possibility of monitoring the working point of PICs by the proposed SPD in order to implement a closed-loop control system.

CONCLUSION

In conclusion, we demonstrated the possibility of monitoring in-line the light intensity in TiO_2 waveguides by exploiting photo-thermal effect in a surface plasmon based detector. The fabricated devices are very compact (1.6 µm long) and their performance in terms of sensitivity (−20 dBm) and speed (>100 kHz) make SPDs good candidate for implementing monitor and control operations in dielectric waveguide platforms, where monolithic integration of semiconductor photodetectors is not a viable approach.

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