All-Silicon, Optics-Free Microspectrometer Chip Based on Vertical Waveguide Array Pixels

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Abstract: We experimentally demonstrate a nanostructured silicon microspectrometer chip that consists of 144 pixels, each comprising an array of vertical waveguides of subwavelength period. We show that both broad- and narrow-band visible spectra can be reconstructed. © 2020 The Authors

1. Introduction

Recent microspectrometer development efforts have moved beyond designs based on the combination of wavelength dispersive elements, such as diffraction gratings or interferometers, with broadband photodetectors. A class of spectrometers employing a filter-free approach, where wavelength selection and photon detection are carried out within the same nanophotonic structure, has emerged [1-3]. Combining these functionalities into a single device is desirable for light-sensing applications where footprint, cost and weight are important factors, such as in handheld personal electronics or on lightweight unmanned aerial vehicles. Here we present a device for which spectral filtering and photon detection occur within the same patterned silicon nanostructure that consists of subwavelength vertical waveguide arrays (WGAs). We experimentally demonstrate the engineering of responsivity spectra of our silicon PIN photodiodes via carefully tailoring the geometric parameters (i.e. waveguide width, s , and array period, Λ) of our WGAs. We fabricate 144 unique WGA pixels on a single chip and, after carefully characterizing each pixel's photoresponse, and developing an appropriate computational spectral reconstruction routine, we demonstrate its functionality as a microspectrometer for both broad- and narrow-band visible test spectra.

2. Results and Discussion

Fig. 1: (a). SEM of a WGA pixel scale bar: 17 μm . Inset: zoom-in of WGA, scale bar: 0.5 μm . (b) Optical micrograph of 108 WGA pixels of the microspectrometer chip. Each colored pixel is 100 μm x 100 μm . (c) Schematic of WGA pixel, with p^+ , $i(n^-)$ and n^+ -doped regions are shown in red, green and blue, respectively. (d) Measured responsivity spectra of $\Lambda=460$ nm WGA pixels, successive curves offset by 0.17 A/W for clarity.

Fig. 1(a) shows an SEM of a fabricated WGA photodetector, prior to the addition of electrical interconnects. For this pixel, waveguides are 220 nm wide. Standard fabrication methods (e beam- and photo-lithography, e-beam evaporation and reactive ion etching) are used, potentially allowing for low-cost fabrication via CMOS-type processes. Fig. 1(b) is a brightfield micrograph of part of the microspectrometer chip, prior to bonding, where 108 of the 144 colorful pixels can be seen. The waveguide widths range from 170 nm to 220 nm. Periods range from 300

nm to 460 nm. A cross-sectional schematic of the WGA pixel with equivalent lumped circuit is shown in Fig. 1(c). The red, green and blue layers represent p^+ , $i(n^-)$ and n^+ -doped silicon regions respectively. Light normally incident on the device can couple directly to waveguide modes without the need for any additional momentum-matching mechanism. The WGA's geometry (s , A) determines the wavelength band for which absorption will be enhanced the active region of the PIN detector. This phenomenon also determines the color of each pixel in the reflected light image of Fig. 1(b). We measure the responsivities of our fabricated WGA detectors by illuminating them with optically chopped light of known power and wavelength. This is provided by a laser driven white light source (Energetiq EQ-99X) coupled to a monochromator (Princeton Instr Acton SP2150). The photocurrents from each pixel vs wavelength at a reverse bias voltage of -1V are measured by a lock-in amplifier (SRS SR830), after a transimpedance amplifier (SRS SR570). Fig. 1(d) shows a set of measured responsivity spectra for WGA pixels of varied widths, with a period of 460 nm. Each pixel has a distinct responsivity spectrum, which is critical for computational reconstruction of test spectra.

Fig. 2: (a) Reconstructed (blue) and reference (red) narrow-band (L1) spectra (b) Set of reconstructed narrow-band (L1) spectra, spanning the visible spectral range. (c) Reconstructed (blue) and reference (red) broad-band (L2) spectra spanning the visible spectral range.

Having characterized each pixel in the microspectrometer chip, it is next possible to estimate unknown spectra from the photocurrents measured from the pixels via a regression algorithm [1, 2]. Here we use two approaches, both based on the least squares method but differing by regularization method. We employ L1- (LASSO) regularization, which is well suited to reconstructing narrowband spectra. For broadband spectra we use L2- (Tikhonov) regularization. Fig. 2(a) shows the good agreement between our L1-estimated spectrum ('FIN144') and the input spectrum measured by a commercial spectrometer (Ocean Optics QE-Pro). Fig. 2(b) shows a set of L1-estimates for narrowband spectra spanning the entire visible range. Our microspectrometer chip is also capable of reconstructing more complicated, broadband spectra, such as the transmission spectrum of a bamboo leaf (Fig. 2(c)). The peak wavelength (of 550 nm), the linewidth and the secondary peak at 450 nm are well represented in our L2-estimate. The latter does not capture the sharp cut-off at $\lambda \sim 650$ nm (due to short-pass filter placed in optical path), however.

3. Conclusion

We have demonstrated the computational spectral reconstruction of broad- and narrow-band spectra across the visible range using an all-silicon nanophotonic microspectrometer chip. The responsivity spectrum of each pixel within the microspectrometer can be engineered by tuning the widths and periods of the WGAs. Our device could find future use in consumer electronics for color-matching, or multispectral imaging and horticultural applications.

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5. References

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