Integrated Silicon-on-Insulator AWG Spectrometer with Single Pixel Readout for 2.3 um Spectroscopy Applications

(Student Paper)

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ABSTRACT

A compact and cheap mid-infrared spectrometer is realized by integrating a Silicon-on-Insulator (SOI) Arrayed Waveguide Grating (AWG) spectrometer operating in the 2.3 µm wavelength range with a high performance photodiode. The AWG has twelve output channels with a spacing of 225 GHz (4 nm) and a free spectral range (FSR) of 3150 GHz (56 nm), which are simultaneously collected by a single, transistor outline (TO)-packaged extended InGaAs PIN photodiode. The response of each AWG channel is discerned by time-sequentially modulating the optical power in each output channel using integrated Mach-Zehnder based (MZI) thermo-optic modulators with a π-phase shift power consumption of 50 mW. The photonic chip is interfaced using off-the-shelf electronic components and a standard 9/125 single-mode fiber. The response of the AWG is limited to one FSR using a 50 nm Full Width Half-Maximum (FWHM) bandpass interference filter. Using 31 µW optical power in the fiber, the absorption spectrum of a 0.5 mm thick polydimethylsiloxane sheet (PDMS) is sampled and compared to a benchtop spectrometer to good agreement.

Keywords: integrated spectrometer, silicon photonics, arrayed waveguide grating, mid-infrared spectroscopy

1 INTRODUCTION

Silicon photonics is expanding its application areas beyond optical communication. In particular, it is possible to access longer wavelengths in the same Silicon-on-Insulator (SOI) waveguide platform for novel compact sensing applications while still leveraging the well-established CMOS fabrication technology [1]. The mid-infrared wavelength range from 2-4 µm is of interest for spectroscopic detection of various substances in solid, liquid or gas phase. There are several approaches towards the realization of a compact and cheap spectroscopic system. For spectroscopy of gases, a high resolution spectrum in a narrow wavelength range is typically required. This can be realized with mid-infrared distributed feedback (DFB) laser sources which can be thermally tuned over a narrow wavelength range [2].
Spectroscopy of liquids and solids involves broad absorption features and an integrated dispersive spectrometer together with detectors and a broadband source would be a more cost-efficient solution. An integrated wavelength (de)multiplexer such as an arrayed waveguide grating (AWG) is needed. The free spectral range (FSR) and channel spacing can be tailored to fit the application. It is possible to heteregeneously integrate III-V-on-Silicon detectors on the photonic IC with the spectrometer [3]. However, existing packaged (cooled) mid-infrared photodetectors currently outperform the on-chip solutions. We present an approach for integrating a single standard TO-can packaged InGaAs PIN photodiode with a twelve channel AWG with 225 GHz (4 nm) channel spacing. The AWG output arms are modulated using on-chip balanced Mach-Zehnder interferometers (MZIs) by thermal tuning [4]. As an example, the absorption spectrum of polydimethylsiloxane (PDMS) in the 2.3 µm wavelength range is recovered.

2 EXPERIMENTS

The AWG is fabricated on a 200 mm SOI wafer with a 400 nm thick crystalline Si device layer and 2 µm buried oxide layer thickness. Rib waveguides and grating couplers are defined with a 180 nm deep etch and are cladded with SiO_2 and planarized down to the silicon device layer. A thin 0.9 µm layer of SiO_x is deposited on top. 100/10 nm thick Ti/Au resistors are defined on the arms of the modulators. The resistors measure 200x2 µm^2 and realize a π-phase shift with $\approx$ 50 mW of power dissipation. As a final step, the chip is passivated with a thin layer of BCB. The circuit is designed for 2.3 µm wavelength and TE polarized light. The AWG has twelve channels with 225 GHz (4 nm) channel spacing and an FSR of 3150 GHz (56 nm). The MZI modulators of the photonic chip are wirebonded to a printed circuit board (PCB) and are addressed by a home-built 16-bit current source through USB. A Hamamatsu G12183-010K PIN photodiode is fixed to a pre-amplifier PCB with a variable gain up to 10^6 V/A. The PD is manually positioned and fixed 0.5 mm above the output grating coupler array of the AWG, see Fig. 1(a). The output grating array covers an area of 300x140

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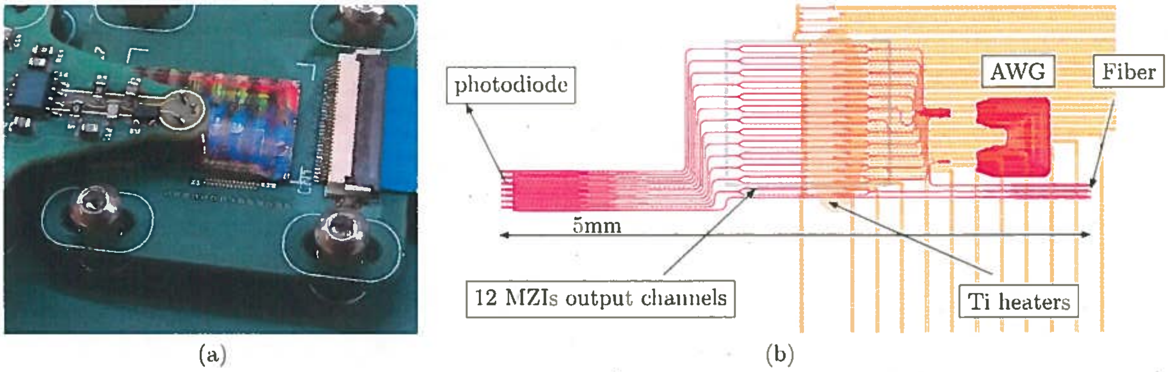

Figure 1. Photograph showing the photonic chip wirebonded to a PCB. The TO-can with the photodiode is positioned directly on top of the output grating couplers of the chip (a). Design layout of the AWG (b). The output channels of the AWG are modulated time-sequentially using (balanced) MZI thermo-optic modulators. A π-phase shift in each channel is achieved by dissipating $\approx$ 50 mW in the metal (Ti/Au) resistor placed 0.9 µm above the optical waveguide.

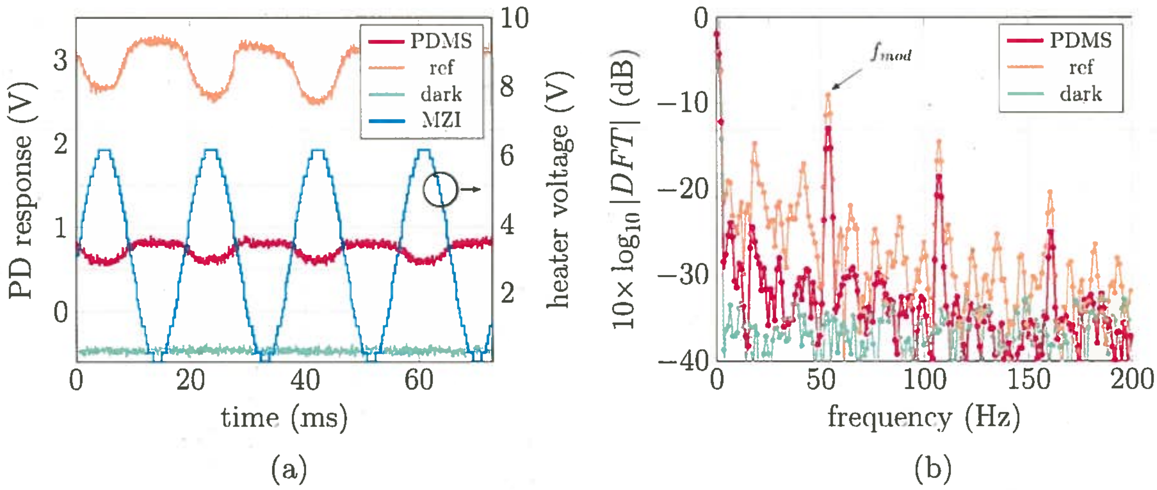

Figure 2. Response of the photodiode to a sinusoidal modulation of one AWG channel. The modulation is done using a MZI thermo-optic modulator. The first thousand sample points are shown for three cases: prior to the chip, the light passes through a 0.5 mm thick PDMS sheet, a reference measurement without PDMS and a dark measurement without the light source (a). The logarithmic DFT spectrum of the PD response is shown (b). The difference in maxima between the 'PDMS' and 'ref' measurement at the modulation frequency f_{mod} is used to determine the spectral response of PDMS at the peak wavelength of this AWG channel.

µm^2 and all the channels are simultaneously collected by the photosensitive area of the PD, 1 mm in diameter. The PD response is read-out using the aforementioned 16-bit ADC with a sampling rate of 24 kSa/s.
A Cr^{2+}:ZnS solid state laser from IPG Photonics working in amplified spontaneous emission (ASE) mode is coupled to a standard 9/125 single mode fiber. The spectrum of the source is filtered in free space prior to coupling using a 50 nm FWHM interference bandpass filter in order to isolate one FSR of the AWG at 2310 nm. After filtering, the total power in the fiber is 31 µW. For the spectroscopy experiment, a 0.5 mm thick Sylgard (1:10) PDMS foil is sandwiched between two 5 mm thick CaF_2 windows and is placed in the free space beam path after the bandpass filter and before the light is coupled into the fiber.
The light from the fiber is vertically coupled to the chip using a grating coupler with a coupling efficiency of 10% at the grating peak wavelength of 2350 nm. The combined output from the channels of the AWG results in a PD signal of 3.2 V for the reference measurement and 0.9 V when PDMS is introduced. The optical power inside each channel can be recovered by modulating each channel time-sequentially [4]. The modulators are nominally transmitting light when no power is dissipated. The modulation depth of the heaters is chosen such that it corresponds to a π-phase shift of each MZI. Slight differences in fabrication lead to drive voltages V_π that are spread between 6 and 7 V and the switching power is about 50 mW. An example of modulation of one such channel is shown in Fig. 2. The PD output is collected for 1 second for each channel with a sampling rate of 24 kHz. The discrete Fourier Transform (DFT) of the signal is performed on the output using the fast-fourier transform (FFT) algorithm with a Kaiser smoothing window. The result for one channel is shown in Fig. 2(b). The absolute value of the DFT spectrum at the modulation frequency is proportional to the optical power modulation of that channel. This value is obtained for each of the twelve channels for the case when

there is no PDMS in the free space beam path and when it is introduced. The difference between the two is a measure for the absorption spectrum of PDMS, sampled at the peak wavelengths of the AWG channels. The AWG channel response is characterized using a single-mode tunable laser and normalized to a reference waveguide. The channel spacing is 225 GHz (4 nm) and one FSR spans 3150 GHz (56 nm). The insertion loss is around 2 dB and the crosstalk between channels is 20 dB.
The absorption spectrum of PDMS obtained in this manner corresponds well to a benchmark measurement. A Yokogawa AQ6375 Optical Spectrum Analyzer (OSA) was used to record the optical spectrum in the fiber before and after introducing PDMS in the free space beam path. The results from the AWG agree well with the OSA measurement, see Fig. 3(b). A slight discrepancy for the longer wavelength channels is observed. This is due to the fact that the central wavelength of the bandpass filter is not exactly centered to one FSR of the AWG.

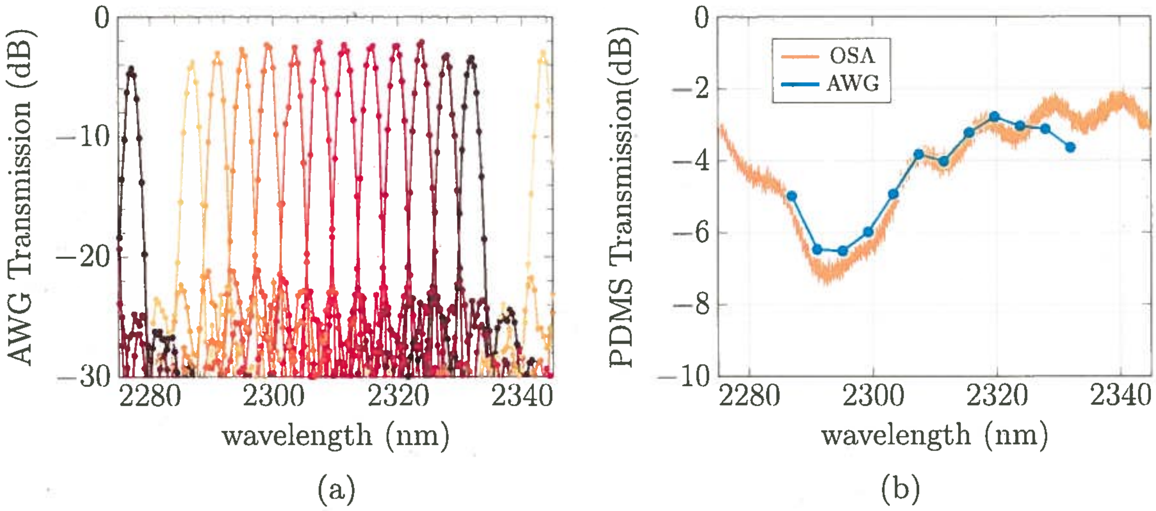

Figure 3. The AWG channels are characterized using a single-mode tunable laser and normalized to a reference waveguide (a). The channel spacing is 225 GHz (4 nm) and one FSR spans 3150 GHz (56 nm). The insertion loss is around 2 dB and the crosstalk between channels is 20 dB. The AWG response is limited to within one FSR with a bandpass filter of 50 nm FWHM at 2305 nm. The optical modulation depth difference of the PD between the PDMS and reference measurement is plotted for each AWG channel with the corresponding channel peak wavelength (b). The results agree well with the results obtained by measuring the PDMS transmission using a Yokogawa AQ6375 OSA.

3 CONCLUSIONS

Low-cost and miniaturized spectrometers can be realized by combining a discrete off-the-shelf mid-infrared photodetector with SOI wavelength demultiplexer circuits. A novel approach is shown where a single discrete photodetector is used to characterize the response of a twelve channel mid-infrared AWG at 2.3 μm. The different AWG channels are discerned by time-sequentially modulating the output arms with MZI-based thermo-optic modulators. The driving and read-out of the spectrometer is performed using low-cost standard electronic components. The absorption spectrum of PDMS is recovered at 2.3 μm to good agreement with bench-top OSA measurements. This is a promising approach which can be applied to longer wavelength SOI spectrometers for the 3-4 μm wavelength range where high-performance cooled detectors are needed.

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