Integrated Spectrometer with Fast Wavelength Scanning Using Current Injection in PIN Diode

Zunyue Zhang
School of Precision Instrument and Opto-Electronics Engineering
Tianjin University
Tianjin, China
zyzhang2023@tju.edu.cn

Kazi Tanvir Ahmmed Rony
Dept. of Electronics Engineering
The Chinese University of Hong Kong
Hong Kong, China
ktarony@cuhk.edu.hk

Yi Wang
Dept. of Electronics Engineering
The Chinese University of Hong Kong
Hong Kong, China
yiwang@link.cuhk.edu.hk

Zhenzhou Cheng
School of Precision Instrument and Opto-Electronics Engineering
Tianjin University
Tianjin, China
zhenzhoucheng@tju.edu.cn

Hon Ki Tsang
Dept. of Electronics Engineering
The Chinese University of Hong Kong
Hong Kong, China
hktsang@ee.cuhk.edu.hk

***Abstract*—We present an integrated spectrometer with fast wavelength scanning. The spectrometer combines a broadband arrayed waveguide grating with a micro-ring resonator which provides high spectral resolution by scanning at up to 300 kHz.**

Keywords—integrated spectrometers, high speed, wavelength scanning, PIN diode, plasma dispersion effect

I. Introduction

Optical spectrometers which have both high spectral resolution and wide optical bandwidth are required for spectral domain optical coherence tomography (SD-OCT)[1]. The spectral resolution determines the imaging depth and optical bandwidth determines the axial imaging resolution of the SD-OCT system[2]. We previously demonstrated an integrated scanning spectrometer, composed of a thermos-optically tuned micro-ring resonator (MRR) and a wideband arrayed waveguide grating (AWG), and showed that it could provide a spectral resolution of 0.2 nm across a 70 nm optical bandwidth[3]. However, due to the relatively slow response of the thermo-optic tuning[4], the wavelength scanning speed was limited to 30 kHz, and was too slow for use in high-speed dynamic OCT imaging systems[5].

In this paper, we improve the wavelength scanning speed of the AWG-MRR integrated spectrometer by an order of magnitude by using electoral current injection into the MRR waveguide. The current injection is facilitated by a lateral PIN diode formed on the waveguide, as shown in Fig. 1(a). By injecting carriers under forward bias, 64 MHz wavelength scanning speed and a wavelength tuning range limited to about half of a free spectral range (FSR) of the MRR was experimentally obtained. Tuning across the full FSR was achieved by switching a micro-heater on the MRR to introduce a resonance wavelength offset of half of FSR. The PIN diode was then used to do high-speed wavelength scanning in each state of the heater to cover the full working wavelength range of the integrated spectrometer. We experimentally measured the spectral resolution of the scanning spectrometer to be 0.1 nm. An integrated array of germanium photodiodes was used to capture the output of the scanning spectrometer.

II. Spectrometer Design

The hybrid current-thermal spectral scanning of the spectrometer is illustrated in Fig. 1(b). The dash lines show the envelops of the AWG channels. The resonance wavelength of the MRR is continuously scanned within the pass band of the AWG channel. The micro-heater is switched between the “on” and “off” states (red and blue solid lines, respectively) to provide a wavelength offset of half of FSR. In each state of the heater, the PIN diode formed on the waveguide is used to continuously scan the resonance wavelength across the half of FSR to obtain the wavelength scanning in the full wavelength range. The integrated spectrometer is designed for fabrication on the silicon-on-insulator (SOI) platform, with 220 nm thick top silicon waveguide layer. The spectrometer was designed to operate with the fundamental transverse electric (TE) mode in the waveguides. The spectrometer comprises two key spectral filters: (A) a 40 channel AWG with 20 nm optical bandwidth; (B) A MRR with a FSR designed to match the channel spacing of the AWG precisely.

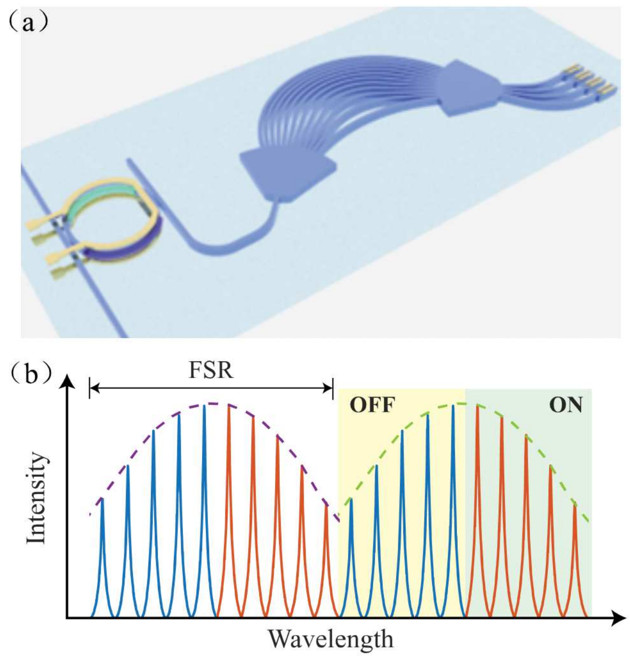

Fig.1 (a) Schematic of the integrated spectrometer. (b) Principle illustration of the integrated spectrometer combining the OFF and ON switch states (blue and red colors) of the thermos-optic heater with the electrical current tuning using the PIN diode.

A. *AWG Design*

The AWG is designed with a channel spacing of 0.5 nm and optical bandwidth of 20nm. The waveguide length increment of the arrayed waveguides is thus designed to be 21.59 μm and the free propagation region is designed to be 369.23 μm in length. There are 150 arrayed waveguides used in the array.

B. *MRR Design*

To match with the channel spacing of the AWG, the MRR is designed with a FSR of 0.5 nm. The bending radius of the MRR is thus calculated to be 135.25 μm. 410 nm wide shallow etched waveguide is used in the design of the MRR. The MRR is designed with both metal heater embedded in the oxide deposited above the MRR and the P/N doping to form a PIN diode for the fast wavelength scanning by current injection. Fig. 2 (a) shows the schematic of the MRR and Fig. 2(b) illustrates the waveguide cross section. When the PIN diode is applied with a forward bias, the carriers are injected to the intrinsic region. The width of the intrinsic region determines the range of the effective index change by the plasma dispersion effect and the range of the resonance wavelength shift induced by the carrier injection. Here we design the intrinsic region width to be 0.8 μm.

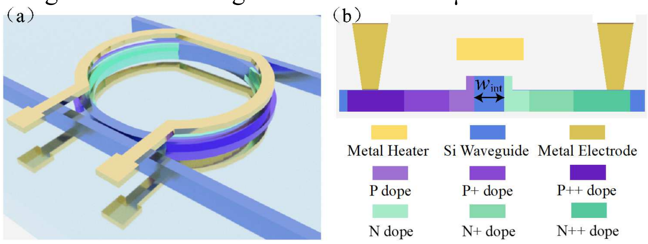

Fig. 2 (a) Schematic of the MRR. (b) Waveguide cross section illustration of the MRR.

III. Experimental Results

The chip was fabricated by Advanced Micro Foundry Pte Ltd, Singapore on SOI multi-project wafer (MPW) platform. The photographs of the chip and the experimental setup is shown in Fig. 3. The measurement of the integrated spectrometer includes the following three part:

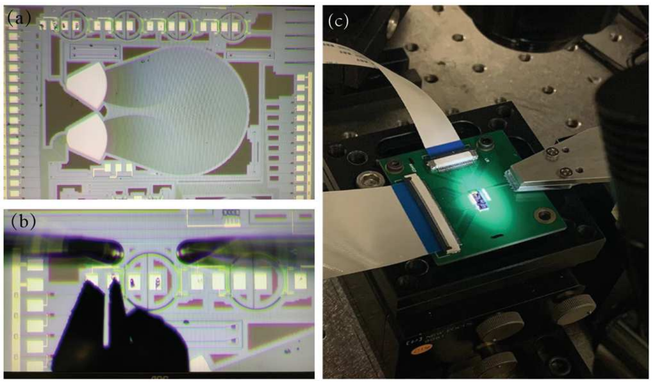

Fig.3 Photos of the chip and experimental setup (a) Integrated spectrometer. (b) Measurement of the wavelength tuning speed. (c) Measurement of the spectral response.

A. *Measurement of the AWG*

The output waveguides of the AWG are connected to 40 on-chip germanium photodetectors. The photocurrent from the photodetector was obtained by measuring the voltage across a 200 kΩ resistance connected in series with the photodetector. The experimental transmission spectrum of the 40 channel AWG is shown in Fig. 4. The channel spacing is measured to be 0.5 nm and the optical bandwidth is measured to be 20 nm, which matches well with the design.

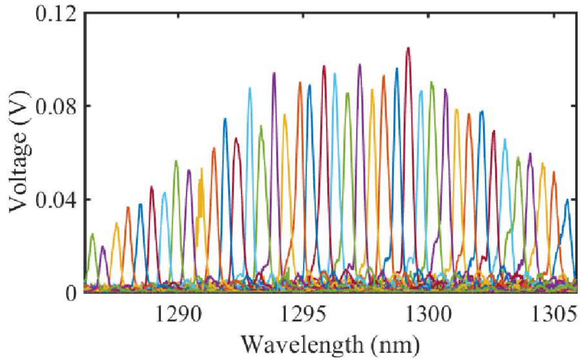

Fig. 4 Experimental transmission spectrum of the 40 channel AWG.

B. *Measurement of the MRR*

The transmission spectrum of the MRR was measured by scanning the wavelength of an O band tunable laser and measure the output optical power of a MRR test structure. The light was coupled into and out of the chip by grating couplers. The experimental setup is shown in Fig. 3(b). The extinction ratio of the MRR was measured to be 15 dB and the insertion loss was about 1 dB. The 3 dB linewidth of the MRR was measured to be 50 pm. The performance of the micro-heater was characterized by measuring the transmission spectrum of the MRR under different driven voltage. The resonance wavelength of the MRR can be tuned by a full FSR, as shown in Fig. 5(a). The wavelength scanning speed was tested by a step-response measurement, which shows 16 μs rising and falling time, as shown in Fig. 5(b), which translates to a 61 kHz tuning speed. Similarly, the performance of the PIN diode was also characterized by adding different driving voltages and measuring the transmission spectrum. The resonance wavelength of the MRR can be tuned by half of FSR with a maximum forward bias of 1.09 V. The carrier injection process under the forward bias introduces extra loss to the MRR and cause the insertion loss variation on the transmission spectrum, as shown in Fig. 5(c). The step-response measurement result of the PIN diode shows a wavelength scanning speed of 64 MHz, as shown in Fig. 5(d).

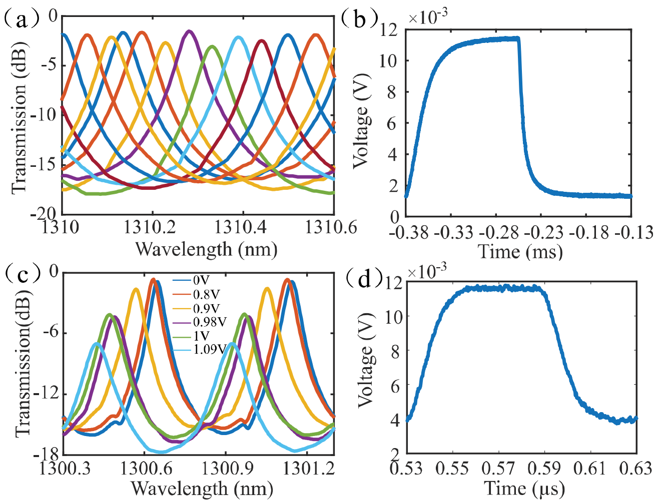

Fig. 5 (a) Wavelength scanning by micro-heater. (b) Step response measurement of the heater. (c) Wavelength scanning by PIN diode. (d) Step response measurement of the PIN diode.

C. *Measurement of the integrated spectrometer*

To extend the wavelength tuning range of the forward biased PIN diode, a micro-heater was used to implement a resonance wavelength offset of half of FSR by switching the heater. In the heater “off” state, no voltage was applied to the heater and there was no wavelength shift. In the “on” state, the heater is driven by the voltage that shifts the resonance wavelength of the MRR by half of a FSR, as shown in Fig. 6(a). In each heater switch state, the PIN diode was used to do fast wavelength scanning across the half FSR, so that the wavelength scanning can be obtained across the full FSR with higher speed than what is possible with just thermos-optic tuning, as shown in Fig. 6(b). Limited by the channel number of the analog to digital conversion (ADC) card used in the experiment, only 16 channels were measured simultaneously. The experimental results are shown in Fig. 6(c) and (d). The insertion loss variation caused by the free carrier absorption can be calibrated and compensated by algorithm in data processing of the SD-OCT for imaging applications. With resonance wavelength tuned by PIN diode by five time in each of the heater state. The effective wavelength scanning speed of the integrated spectrometer over 300 kHz.

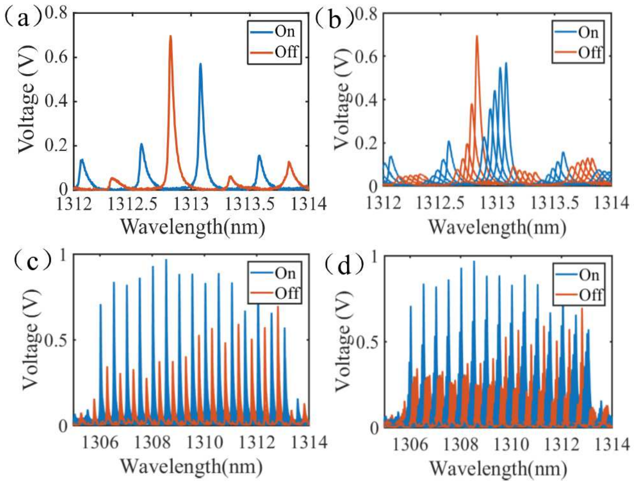

Fig. 6 (a) Transmission spectrum measured from one single channel in “on” and “off” states of the heater. (b) Transmission spectrum measured from one single channel with wavelength scanning by PIN diode in two heater states. (c) Transmission spectrum measured from 16 channels in “on” and “off” states of the heater. (d) Transmission spectrum measured from 16 channels with wavelength scanning by PIN diode in two heater states.

IV. Conclusion

In this paper, we proposed and demonstrated an integrated spectrometer with a wavelength scanning rate of over 300 kHz by using a broadband AWG integrated with a tunable MRR. The resonance wavelength of the MRR is scanned by combing electrical current injection into a PIN diode and switching a micro-heater on the MRR. Wavelength scanning across the full working wavelength range of the AWG with 0.1 nm effective spectral resolution was experimentally obtained. Integrated germanium photodetector array was used to capture the high-speed spectral scanning outputs from the AWG. The high-speed scanning spectrometer will facilitate the further development of integrated high-resolution and broadband spectrometers for dynamic OCT imaging systems.

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