A Silicon Photonic Integrated Frequency-Tunable Optoelectronic Oscillator

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***Abstract*—A silicon photonic integrated frequency-tunable optoelectronic oscillator (OEO) is designed, fabricated and experimentally demonstrated. Three key components including a high-speed phase modulator (PM), a thermally-tunable high-Q micro-disk resonator (MDR), and a high-speed photodetector (PD) are monolithically integrated on a silicon photonic chip. The joint operation of the PM and the MDR corresponds to a microwave photonic filter (MPF) with an ultra-narrow notch that is thermally tunable. By feeding the output signal from the MPF to its input port through an electrical amplifier to provide a sufficiently large gain, the MPF becomes an OEO and oscillation starts. A microwave signal with a frequency tunale from 3 to 7 GHz is generated. The phase noise of a generated microwave signal at 5.4 GHz is measured to be -80 dBc/Hz at an offset frequency of 10 kHz.**

Keywords—Microwave photonic filter, optoelectronic oscillator, integrated microwave photonics, silicon photonics, micro-disk resonator, phase modulation to intensity modulation conversion

I. Introduction

Generation of high frequency and ultra-low phase noise microwave signal using an optoelectronic oscillator (OEO) is considered an effective solution [1-3], which can find numerous applications such as in wireless communications, radar, modern instrumentation, microwave imaging, and microwave spectroscopy [4]. To ensure an OEO operates in single mode, a high-Q bandpass filter must be used. In earlier demonstrations, the high-Q bandpass filter is an electrical BPF. The use of an electrical BPF has two limitations. First, an electrical BPF is not tunable or with a very small tunable range, thus a microwave signal with a fixed frequency or a small frequency tunable range can be generated [5, 6]. Second, a high frequency electrical BPF usually has a large bandwidth. To ensure single frequency operation, the bandwidth must be small, which would limit the highest operating frequency. To overcome these two limitations, a solution is to use a microwave photonic filter (MPF) [7-9]. An MPF can have a high center frequency while maintaining a small 3-dB bandwidth. However, most of the OEOs using an MPF are implemented based on discrete optical components, which makes the system bulky, expensive and high-power consumption. For many applications, it is highly desirable that an OEO could be implemented using a photonic integrated circuit (PIC) [10]. Recently, silicon photonic integration with advantages including compact footprint and simple and low-cost fabrication [11] has been extensively studied for microwave photonic system implementations and many results have been reported [12, 13]. But, to the best of our knowledge, no integrated OEO on a single silicon chip has been reported.

In this paper, we report the design, fabrication and experimental demonstration of a silicon-photonic integrated frequency-tunable OEO. Three key components including a high-speed phase modulator (PM), a thermally-tunable high-Q micro-disk resonator (MDR), and a high-speed photodetector (PD) are monolithically integrated on a silicon photonic chip, and are fabricated using the CMOS-compatible technology. Thanks to the ultra-narrow notch and thermal tunability of the MDR, the MPF has a narrow and tunable passband, which plays a key role when used in an OEO to perform frequency selection and frequency tuning. In our experimental demonstration, a bandpass MPF with a 3-dB bandwidth of 1.8 GHz and a frequency tuning range from 3 to 7 GHz is first realized. Then, by feeding the output signal from the MPF to its input port through an electrical amplifier to provide a sufficiently large gain, the MPF becomes an OEO and starts to oscillate. A frequency-tunable microwave signal with a frequency tunable from 3 to 7 GHz by thermal tuning is generated. The phase noise is measured to be -80 dBc/Hz at an offset frequency of 10 kHz. The successful demonstration of an integrated OEO is a major step forward to achieve full integration of microwave photonic systems for applications in wireless and radar systems.

II. Principle of Operation

Fig. 1(a) illustrates the schematic of the proposed silicon photonic integrated frequency-tunable OEO. It consists of three key components including a high-speed PM, a thermally-tunable high-Q MDR, and a high-speed PD. A CW light from an external laser diode (LD) is fiber coupled into the chip via an input grating coupler and is guided to the high-speed PM, where the incoming microwave signal is modulated on the CW light. At the output of the PM, a phase-modulated optical signal is generated and it is sent to the high-Q MDR, which serves as an optical notch filter. A compact Y-branch coupler is connected to the output of the MDR to split the optical signal into two channels. One channel is routed to an output grating coupler to couple the light out of the chip for real-time optical spectrum monitoring. The other channel is applied to the high-speed PD, where optical to electrical conversion is performed. If the phase-modulated optical signal is directly applied to the PD without using an MDR, no microwave signal will be generated except a DC. If one of the two sidebands of the phase-modulated optical signal falls in the notch of the MDR,

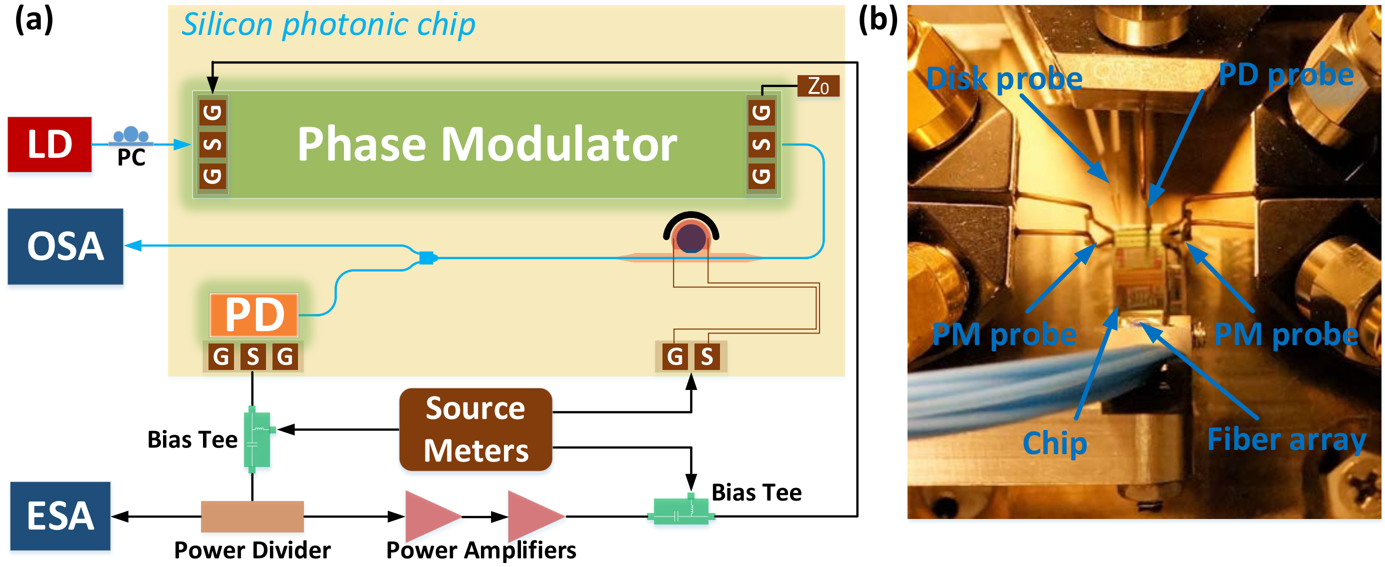

Fig. 1 (a) Schematic of the proposed integrated frequency-tunable OEO on a silicon photonic chip. LD: laser diode LD, PC: polarization controller, OSA: optical spectrum analyzer, ESA: electrical spectrum analyzer; (b) a picture of the text set-up.

the phase-modulated signal is converted to an intensity-modulated signal, and the microwave signal will be recovered at the PD. The entire operation corresponds to a bandpass MPF with the spectral response of the microwave bandpass filter translated from the spectral response of the optical filter. Thanks to the ultra-narrow notch and thermal tunability of the MDR, the MPF has a narrow passband and is tunable. By feeding the microwave signal at the output of the MPF to its input through an electrical amplifier with a sufficiently large gain, the MPF becomes an OEO and microwave oscillation starts. By tuning the notch of the MDR, the center frequency of the MPF filter is tuned, and thus the frequency of the generated microwave signal is tuned. Fig. 1(b) shows a picture of the test set-up, with the chip shown in the center of the picture. Thanks to the high-level integration of the chip, the set-up is simple, which makes the system to have stable operation and low power consumption.

III. Experiment

First, the frequency response of the frequency-tunable bandpass MPF is measured. To do so, the loop is opened at the output port of the PD, and a vector network analyzer (VNA, Agilent E8364A) is used to measure frequency response of the MPF. The optical carrier generated by the LD has a wavelength of 1537.88 nm and a power of 15 dBm, and a polarization controller (PC) is used to adjust the state of polarization (SOP) of the light to the PM, to minimize the polarization-dependent loss. A pair of microwave probes with GSG configuration is used to apply a microwave signal from the VNA to the PM, a microwave probe with GSG configuration is used in combination with a bias tee to apply a reverse bias voltage to the PD and to collect the recovered microwave signal from the PD, and a DC bias probe is used to apply a DC current to the micro-heater for wavelength tuning. When the frequency of the microwave signal is equal to the frequency difference between the optical carrier and the notch center, the upper sideband falls into the notch of the MDR and is removed, the phase modulated signal is converted to an intensity-modulated signal, and an MFP with a notch is implemented. By tuning the notch of the MDR, the center frequency of the bandpass MPF is tuned. Fig. 2(a) shows the measured magnitude response of the MDR. As can be seen, the notch has a 3-dB bandwidth of 11 pm, corresponding to a Q-factor of 1.4×10^5. Fig. 2(b) shows the measured frequency response of the bandpass MPF at a center frequency of 5.84 GHz. The MPF has a 3-dB bandwidth of 1.8 GHz and an extinction ratio of 17 dB. By thermally tuning the MDR, the center wavelength of the notch is laterally shifted. Fig. 2(c) shows the measured frequency responses of the MPF with its center frequency tuned from 3 to 7 GHz when a tunable DC current is applied to the micro-heater. The power consumption is calculated to be 0.675 mW, which is small. Thus, the two key advantages, broad frequency-tunable range and low power consumption, have been validated.

Note that the peak power of the frequency response is becoming smaller with the increase of the center frequency, as can be seen from Fig. 2(b), which is caused by the limited bandwidths of the PM and PD.

Then, by feeding the microwave signal at the output of the PD to the input port of the PM through an electrical amplifier with a gain larger than the loop loss, the MPF becomes an OEO and starts to oscillate. The oscillation frequency of the OEO could be tuned by tuning the center frequency of the MPF via applying the different bias voltage to the micro-heater. In the experiment, two microwave amplifiers (Agilent 83050A and MultiLink modulator driver MTC5515-751) are used to provide a sufficiently large gain. Fig. 3(a) shows the measured electrical spectrum of the generated microwave signal at 5.4 GHz, where the frequency span is 40 GHz and the resolution bandwidth (RBW) is 200 KHz. As can be seen, higher-order harmonics could be observed, which is caused by the nonlinearity of the OEO loop. Fig. 3(b) shows the electrical spectrum of the generated 5.4-GHz signal with a frequency span of 4 GHz and a RBW of 200 KHz. The inset gives a zoom-in view of the electrical spectrum with a frequency span of 20 MHz and a RBW of 180 KHz. As can be seen a side-mode suppression ratio (SMSR) as high as 57 dB is obtained.

Fig. 3(c) shows the measured optical spectrum at the output grating coupler of the chip when the OEO is operating at 5.4 GHz. It is clear to see that the power of the upper first-order sideband is smaller than that of the lower first-order sideband by 3.8 dB. Although the upper sideband is not completely removed, the residual power is very small, and an effective phase-modulation to intensity-modulation conversion is achieved.

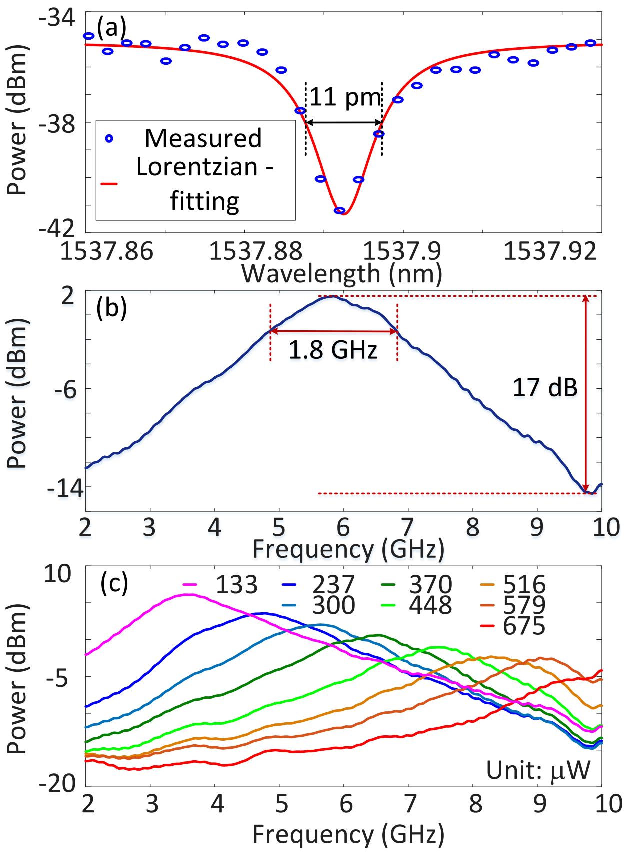

Fig. 2. (a) Measured magnitude response of the MDR; (b) measured frequency response of the MPF with a center frequency of 5.84 GHz; (c) measured frequency responses of the MPF with its center frequency tuned from 3 to 7 GHz.

The frequency tunability of the proposed OEO is then investigated. By tuning the bias voltage to the micro-heater, the notch of the MDR is shifted and thus the frequency of the generated microwave signal is tuned. Fig. 4 shows the superimposed spectrums of the generated microwave signal with its frequency tuned from 3 to 7 GHz. As can be seen, with the frequency of the generated microwave signal tuned, a high SMSR is still maintained. Since the MPF has a lower gain at a higher frequency and the two microwave amplifiers could not offer an enough gain to support the OEO to operate at a frequency higher than 7 GHz, the frequency tunable range is limited to 3 to 7 GHz in this experimental demonstration.

Fig. 5 shows the measured phase noise of the generated microwave signal when the OEO is operating at 5.4 GHz. The phase noise at a 10-KHz offset frequency is measured to be -80 dBc/Hz, which is quite large. Since the chip has a small footprint, the OEO has short loop length, which leads to a high phase noise. The phase noise performance can be improved by adding an optical waveguide delay line on the chip or by designing an MDR with a higher Q factor.

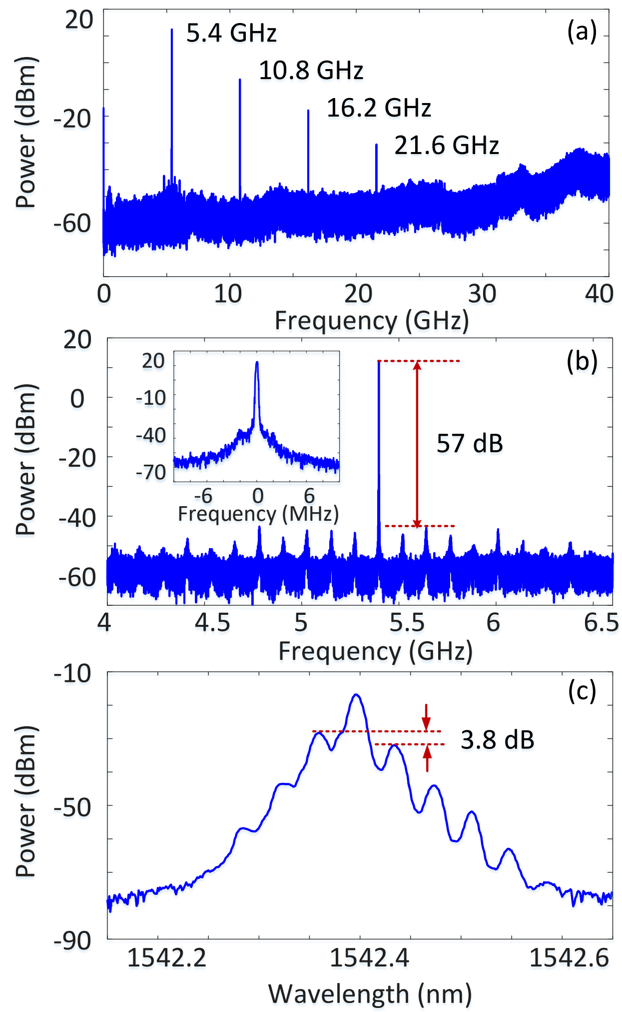

Fig. 3 (a) Electrical spectrum of the generated 5.4 GHz signal (the frequency span is 40 GHz and the resolution bandwidth (RBW) is 200 KHz); (b) electrical spectrum with a frequency span of 4 GHz and a RBW of 200 KHz. Inset shows a zoom-in view of the electrical spectrum with a frequency span of 20 MHz and a RBW of 180 KHz; (c) measured optical spectrum at the optical output grating coupler when the OEO is operating at 5.4 GHz.

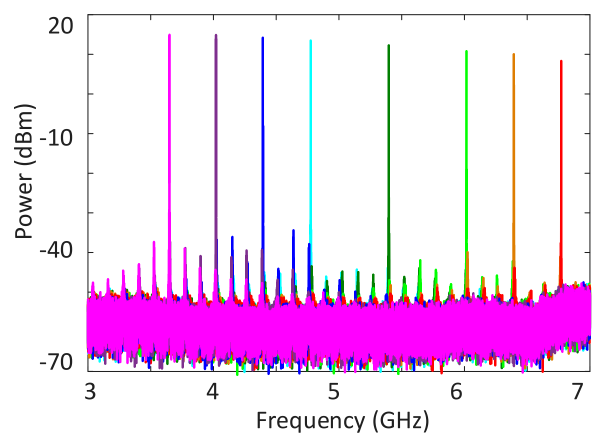

Fig. 4 Measured electrical spectrums of the generated microwave signal at different frequencies. The frequency is coarsely tuned from 3 to 7 GHz and the RBW is 200 KHz.

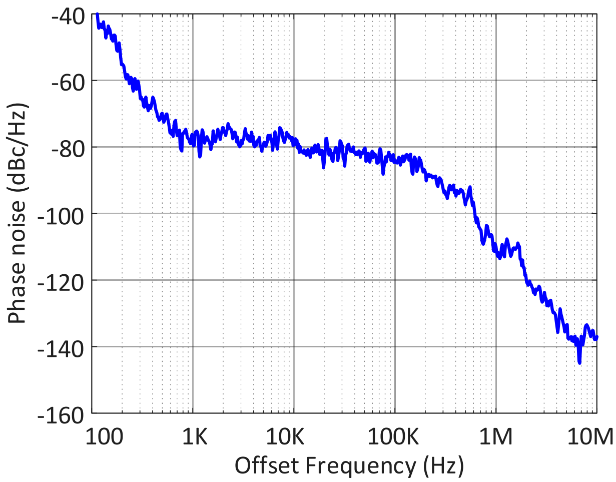

Fig. 5. Measured phase noise of the proposed OEO when the OEO is operating at 5.4 GHz.

IV. SUMMARY

An silicon photonic integrated frequency-tunable OEO was designed, fabricated and experimentally demonstrated. A microwave signal with a frequency tuanble from 3 to 7 GHz was generated. The phase noise was measured to be -80 dBc/Hz at an offset frequency of 10 kHz.

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