Microwave Frequency Identification System using a high-Q Mach-Zehnder interferometer (MZI) coupled micro-ring resonator

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***Abstract*—We present a microwave frequency identification system utilizes a high Q-factor Mach-Zehnder interferometer (MZI) coupled micro-ring resonator (MZI-coupled MRR), which employs ultra-low-loss waveguides and Euler curve techniques. This system maps frequency information to the time domain, allowing for identification of unknown single and multi-frequency signals. Our system demonstrates a broadband microwave frequency measurement ranging from 0-40 GHz, accompanied by a measurement error of 392.6 MHz, and the ability to capture multiple frequencies simultaneously.**

Keywords—frequency identification, dual-parallel Mach-Zehnder modulators, micro-ring resonator, multi-frequency measurement

I. Introduction

Accurately identifying the frequency of unknown intercepted microwave signals is crucial in fields such as radar warning receiving[1], electronic intelligence systems[2], and radio astronomy [3]. As these systems advance towards high frequency, broadband, and multiband operation, photonic microwave identification systems have been extensively studied and offer superior performance in terms of flexible reconfigurability and wide bandwidth compared to traditional electronic counterparts.

One promising method for instantaneous frequency measurement of unknown signals is the frequency-to-power mapping (FTPM) approach, which constructs an amplitude comparison function using tunable filters such as Fabry-Perot etalons, fiber Bragg gratings [4], and MZIs [5]. However, achieving a wide measurement range, high precision, and the ability to measure multiple frequencies simultaneously is a challenge with these techniques. In contrast, the frequency-to-time mapping (FTTM) scheme allows for statistical measurement of multiple frequencies [6]. Due to their compact footprint and convenient reconfigurability, micro-ring resonators (MRRs) have gained recognition as one of the most attractive options for implementing frequency identification systems among various architectures.

Recently, a high-Q (3.974×10^3) add-drop MRR has been demonstrated to measure microwave frequency from 0.5 GHz to 35 GHz with a measurement error of 300 MHz; the measurement errors can be improved to 60 MHz using improved high-Q add-drop MRR (2.58×10^4) at the scarification of the measurement frequency range because of the reduced FSR [7]. What' s more, an add-drop MRR can be used to identify different types of microwave signals from 10 GHz to 20 GHz with a root-mean-squares error of ≈ 409.4 MHz [8]. It can be observed that the measurement frequency range and error is directly correlated to the FSR and 3-dB bandwidth of the MRR. Thus, it is highly desirable to develop high-performance MRR with a high-Q factor and a large FSR. More recently, the introduction of ultra-low-loss multimode waveguide bends (MWBs) technology with modified Euler-curve structures has helped to implement an MRR with an ultra-high loaded Q-factor of 1.3×10^6 and an FSR as large as 113 GHz [9]. This is the smallest MRR with Q-factor over 1×10^6, which is very attractive for realizing high-performance microwave frequency identification.

In this paper, we propose a compact design of U-bend-MZI-coupled MRRs based on modified Euler-curve MWBs for photonic microwave frequency identification system. The proposed U-bend-MZI-coupled MRR has a high Q-factor (1.3×10^6) as well as a large FSR (0.9 nm), enabling a large frequency-tuning range. What's more, the coupling coefficient of the MRR can be tuned to achieve a optimally 3-dB bandwidth and extinction ratio (ER). Using this device, we demonstrate a broadband frequency measurement system ranging from 0 to 40 GHz with a root- mean-squares error of 392.6 MHz . The measurement error can be further improved to155 MHz and frequency range can be improved to 100 GHz using high-speed optical-electrical devices and more stable experimental set-up. Furthermore, the system has demonstrated the ability to accurately measure multiple frequency signals. Our system paves the way for high-performance microwave frequency identification systems.

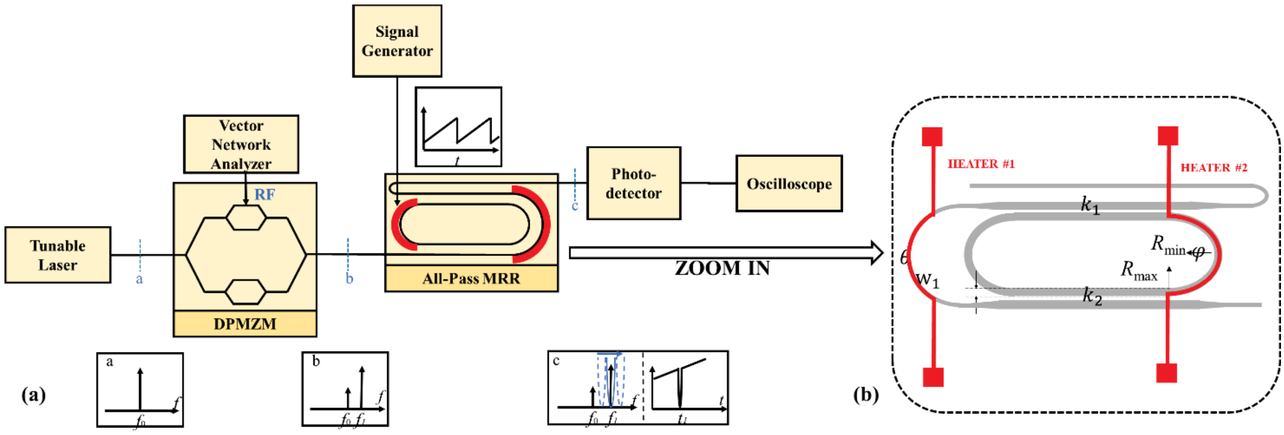

Fig.1. (a) Schematic of the photonic microwave frequency identification system with a thermally tunable MZI-coupled MRR; (b) Schematic of the proposed high-Q MZI-coupled MRR.

II. DEVICE DESCRIPTION

A. *Principal*

Fig. 1(a) depicts the operational principle of the proposed photonic microwave frequency identification system utilizes a U-bend-MZI-coupled MRR. Initially, the optical signal (f_0) from a tunable laser is modulated via single-sideband modulation using the DPMZM, driven by RF signals of unknown frequency (f_1). The modulated signal is then processed by the U-bend-MZI-coupled MRR, which filters the signal periodically with a sawtooth voltage from the signal generator applied on heater #2 of the MRR to alter its resonant wavelength. When the resonant frequency of the U-bend-MZI-coupled MRR match the sideband frequency, f_1, the signal will be filtered out and no signal will be received by the PD. Otherwise, the signal will directly transmit and received by the PD. In this way, the time-domain spectrum on the oscilloscope will be capture the power change and the corresponding time information can be mapped to the frequency domain to measure the microwave frequency. Similarly, this technology can also be used in the multi-frequency measurement system.

Fig. 1 (b) show the structure of U-bend-MZI-coupled MRR based on ultra-low-loss MWB and modified Euler curve techniques. A micro-heater (heater #1) is placed on the MWB in order to thermally tune the phase, θ. For preciously control the coupling coefficient, k, a U-bend MZI coupler is introduced with a thermally-tunable phase-shifter (heater #2) in one of its arms. The details of the design principle is in Ref. [10]. In order to achieve a high Q-factor and large FSR of the U-bend-MZI-coupled MRR at the same time, we choose the multimode waveguide width as 2 µm, the loss can be approximately reduced to 0.28 dB/cm. The bending radius of Euler-curve is set as $R_{\max}$ = 600 µm and R_{min} = 15 µm, respectively. The MRR has a high-Q factor of approximately 1.3×10^6 and a free spectral range (FSR) of 113 GHz.

B. *Chip Structure*

Fig. 2 (a) shows the chip picture of the MZI-coupled MRR on silicon. The overall chip size is approximately 460 µm × 80 µm, and the incidence angle of the grating coupler is optimized at 8°. The characterization results are in Fig. 2(b) and 2(c). In Fig. 2 (b), only the resonances corresponding to the fundamental mode are observed, indicating that higher-order modes are suppressed very well in the MRR with MWBs. The measured FSR is about 113 GHz (i.e., 0.9 nm), which matches the simulation result. As we can see from zoom-in resonance in Fig. 2(b), the 3-dB bandwidth is around 1.2 pm. The resonance wavelength of the MRR shifts by 0.9 nm when the DC voltage changes from 0 V to 4.1 V on the phase shifter. Furthermore, Fig. 2 (c) presents the corresponding and fitting curve of MRR transmission without applied voltage. The device processing only requires a simple standard process provided by a multi-project wafer foundry, without any special fabrication process.

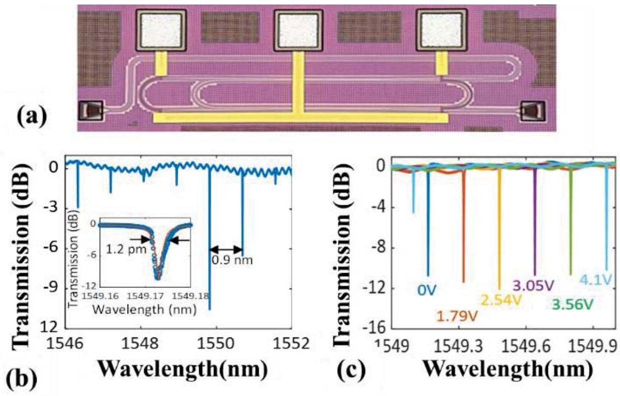

Fig. 2. (a) Micrograph of the high-Q U-bend-MZI-coupled MRR; (b) the transmission of the U-bend-MZI-coupled MRR, and enlarged view of the measured fundamental mode resonance peak; (c) the spectrum tuning of the U-bend-MZI-coupled MRR as the voltage applied on the micro-heater (#2) increases.

III. EXPERIMENT RESULTS

A. *Single Frequency Identification*

A periodic sawtooth voltage ranging from 20 to 180 mV with a period of 10 ms is applied on heater#2 of the U-bend-MZI-coupled MRR, as illustrated in Fig. 3(a). RF signals with different frequency spacings of 200 MHz, 50 MHz, and 10 MHz around 0.1GHz are tested and the corresponding time-domain signals were obtained, as depicted in Fig. 3(b)-(d). The RF signals with frequency spaces of 200 MHz and 50 MHz in Fig. 3(b) and 3(c) can be distinguished clearly, whereas RF signals with a frequency spacing of only 10 MHz in Fig. 3(d) is difficult to distinguish. The contribution from the linewidth of the laser that determines the lower resolution of the low frequency.

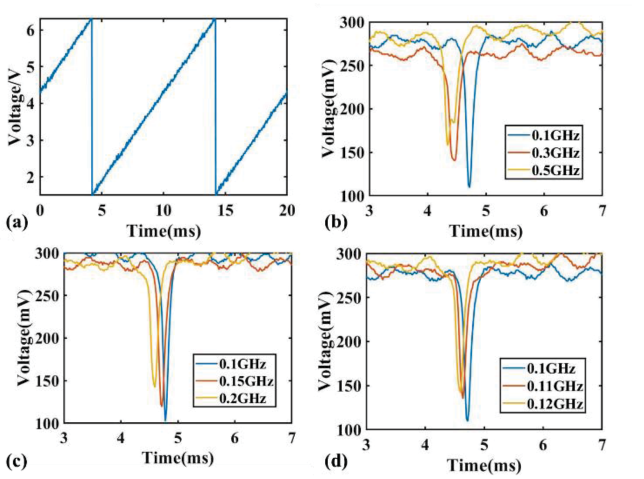

Fig.3. (a) The periodic sawtooth voltage generated by the signal generator;(b) Time domain spectrum obtained by oscilloscope when RF signal difference is 100 MHz;(c) Time domain spectrum obtained by oscilloscope when RF signal difference is 50 MHz;(d) Time domain spectrum obtained by oscilloscope when RF signal difference is 10 MHz.

Using thermal-tuning mechanism tuning elements, the resonance shift is directly proportional to the applied electrical power, and quadratic to the voltage over time. To determine the mapping function between delay and RF frequency, we tested and fitted a set of frequencies ranging from 0.01 to 40 GHz limited by the available RF signal generator. The mapping relationship between the delay and RF frequencies is shown in Fig. 4(a). Fig. 4(b) shows the RF frequency estimated using the setup in Fig. 1(a) versus the actual input frequency for each of the test RF signals, as well as the measurement error. It illustrates that the system has the ability of broadband microwave frequency measurement from 10 GHz to 40 GHz, and can be extended to 100 GHz with higher-speed RF devices. The corresponding mean error is 347.7MHz and the root-mean-square error is approximately 392.6 MHz. Normally, the measurement error is mainly due to the resolution of the MRR, therefore, our MZI-coupled MRR with high resolution can improve the measurement error with more stable experimental setup.

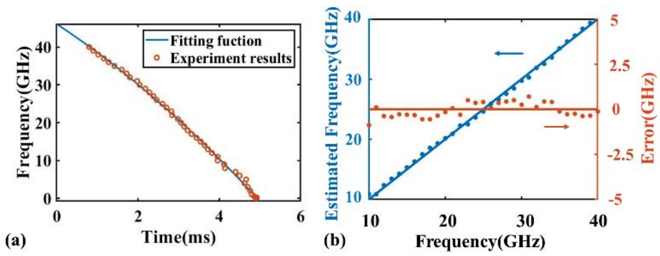

Fig.4. (a) The relationship between the delay and the RF frequencies needed to be measured. (b) Estimated frequency (blue dots) and corresponding error (red dots) using the experimental set-up in Fig. 1(a).

B. Multi Frequency Identification

In practical, it is often necessary to measure multiple RF frequencies, simultaneously. To test the system's capability of measuring multiple RF frequencies, different random combinations of two-tone signals or three-tone signals are input into the DPMZM, set as 25 and 28 GHz, 18, 33 and 36 GHz, respectively. By driving the resonance-sweeping MZI-coupled MRR with a periodic sawtooth voltage, two/three clear pulses were observed on the oscilloscope, as depicted in Fig. 5(a) and 5(b). The actual measured values are labeled in the diagram and the error is small, indicating that this system is capable of performing multi-frequencies measurement.

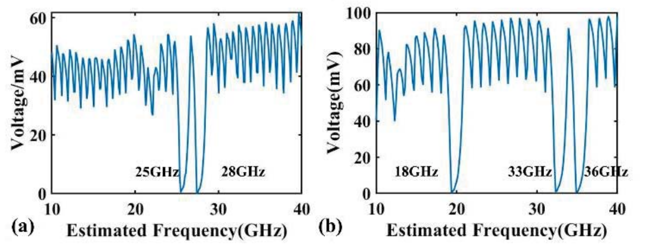

Fig.5. Measurement results of multi-frequency signals with different tones (a) 25, 28 GHz; (b)18, 33, 36 GHz.

IV. CONCLUSION

We have developed a microwave frequency identification system utilizes a high-Q MZI-coupled MRR using ultra-low loss silicon waveguide and Euler-curve techniques. The system achieves frequency identification by mapping frequency information to the time domain with a wide operating bandwidth of 0-40 GHz with a root-mean-square error of 392.6 MHz, and also capable of identifying multi-frequency signals with different tones.

ACKNOWLEDGMENT

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