A Frequency-tunable Two-tone RF Signal Generator by Polarization Multiplexed Optoelectronic Oscillator

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***Abstract*— A two-tone radio frequency (RF) signal generator realized by a polarization multiplexed optoelectronic oscillator (OEO) is proposed and demonstrated. The OEO employs a dual-polarization modulator and can simultaneously generate two frequency tones through OEO oscillations in two orthogonal polarizations of the same optical carrier. Frequencies of the two tones can be tuned independently by adjusting the electrical filters. Advantage of the proposed system is that, the optical interference between two-tone oscillations is effectively suppressed by polarization isolation and the multi-frequency intermodulation in a single modulator is avoided, which leads to the generation of a high quality two-tone RF signal. In the experiment, a two-tone signal at 9.95GHz and 10.66 GHz is generated with a phase noise (@10kHz) of −105.06 dBc/Hz and −104.43 dBc/Hz, respectively. The frequency tunability of the two-tone signal generator is also demonstrated in a range from 4 GHz to 12 GHz.**

***Index Terms*— Microwave photonics, optoelectronic oscillator (OEO), polarization multiplexing, two-tone signal.**

I. Introduction

TWO-tone radio frequency (RF) signals have significant applications in modern electronic systems. For example, to test the linearity of a RF device or system, a two-tone signal is required [1]. In this application, the two-tone RF signal should have a high frequency resolution and a low phase noise to realize precise measurement. High-quality two-tone RF signals can also be used as local oscillators in reconfigurable dual-band radar and communication systems [2], where frequency tunability across different frequency bands is highly desirable. The two-tone signals generated by pure electrical technologies usually suffer from low frequency, small frequency-tuning range and poor phase noise (especially at high frequencies). Optoelectronic oscillator (OEO) has been proposed as a promising solution to generate RF signals with excellent spectral purity and ultra-low phase noise [3], [4]. However, most of the reported OEOs are focused on single-frequency RF signal generation. By simply applying two independent OEOs, two-tone RF signals can be generated, but the cost and complexity would be very high. In [5], T. Sakamoto *et al* proposed a two-tone signal generator based on an OEO using a push-pull Mach-Zehnder modulator (MZM) biased at the null point. The shortcoming is that the frequencies of the two tones have a fixed ratio of 2:1. Another OEO-based two-tone signal generator is implemented by multi-channel phase-modulation to intensity-modulation conversion [6], in which multiple tunable lasers and narrow band optical notch filters are required. Thus, the system is still complicated. In [7], F. Kong *et al* demonstrated a two-tone OEO using a phase-shifted fiber Bragg grating (PS-FBG). The system is simple, but sensitive to the environment, making the frequencies hard to be controlled. Another simple two-tone OEO using a single MZM is demonstrated in [8], where different frequency components are selected and amplified separately in electrical domain before they are combined to drive the MZM. The main problem is the intermodulation due to multi-frequency modulation in a single modulator, which would deteriorate the spectral purity of the two-tone RF signal.

In this letter, we propose and demonstrate a polarization multiplexed OEO to generate frequency tunable two-tone RF signals. The proposed OEO can simultaneously oscillate at two frequencies with a compact structure. The frequencies of the generated two tones can be adjusted independently by tuning the electrical filters. Since the two-tone oscillations are established along the two orthogonal polarizations of the same optical carrier, the optical interference between the two oscillations can be well suppressed and thus the system stability will be enhanced. Besides, the electro-optical modulations at different frequencies are performed by two sub-modulators in an integrated dual-polarization modulator. This helps to obtain a clean two-tone RF signal because the multi-frequency intermodulation in a single modulator is eliminated.

II. Principle

Fig. 1 shows the schematic diagram of the proposed two-tone signal generator based on a polarization multiplexed OEO. The key component is an integrated dual-polarization modulator, which is commercially available and was initially designed to generate polarization multiplexed optical signals in optical communication systems [9]. The dual-polarization modulator consists of two parallel Mach-Zehnder

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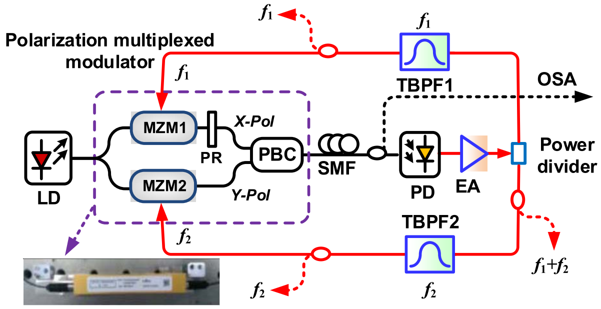

Fig. 1. Schematic diagram of the proposed two-tone RF signal generator. LD: laser diode, MZM: Mach-Zehnder modulator; PR: polarization rotator; PBC: polarization beam combiner; SMF: single mode fiber; PD: photodetector; EA: electrical amplifier, TBPF: tunable band pass filter.

modulators (MZM1 and MZM2), a polarization rotator (PR) and a polarization beam combiner (PBC). The continuous wave (CW) light from a laser diode (LD) is directed to the dual-polarization modulator and split into two branches with equal power. The separated two optical carriers are modulated by MZM1 and MZM2, respectively. The two sub-MZMs are both biased at the quadrature point such that the even-order harmonics are suppressed after optical-to-electrical conversion. After MZM1, the polarization direction is rotated by 90° at the PR. Then, the two optical signals in two orthogonal polarizations are combined at the PBC to generate a polarization multiplexed optical signal. The output signal from the dual-polarization modulator passes through a span of single mode fiber (SMF) which provides the time delay required in an OEO. After that, the optical signal is converted to an electrical signal at a photodetector (PD). The generated electrical signal is amplified by an electrical amplifier (EA) and then separated into two parts by a 3-dB power divider. In each branch, the electrical signal goes through a tunable bandpass filter (TBPF1 and TBPF2). To complete the OEO loops, the two selected electrical signals are applied to drive MZM1 and MZM2, respectively. After stable oscillation is established, a specific frequency tone can be generated in each OEO loop, and the two frequencies can be adjusted independently by tuning the central frequency of the TBPFs. The RF signal in each loop can be exported by an electrical coupler after the TBPF.

In the proposed OEO, the laser source, the dual-polarization modulator, the SMF, the PD and the EA are all shared by the two-tone oscillations, thus the proposed system is compact and cost-effective. Another property of the polarization multiplexed OEO is that, the two frequency tones oscillate along two orthogonal polarizations of the same optical source. This not only saves the use of multiple lasers but also enhances the output stability because the polarization isolation can effectively suppress the optical interference between the two frequencies. Besides, in the proposed OEO, electrical feedbacks at different frequencies are implemented by two sub-modulators. Therefore, multi-frequency intermodulation in a single modulator is avoided, and the generated two-tone RF signal is expected to have a good spectral purity.

III. Experimental Demonstration

In the experiment, a CW light at 1556 nm is generated by an LD (SANTUR TL-2020-C) with a power of ∼10 dBm.

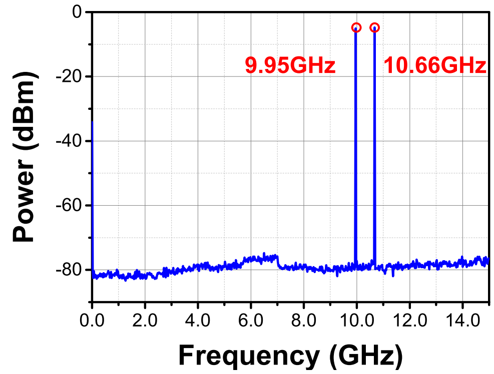

Fig. 2. The measured electoral spectrum (RBW: 10 KHz) of the two-tone RF signal at 9.95 GHz and 10.66 GHz generated from the proposed structure.

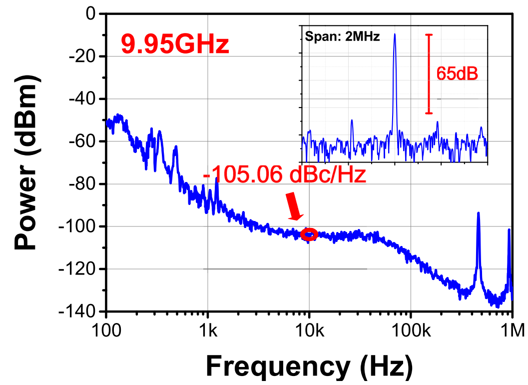

Fig. 3. Measured single-sideband phase noise of the 9.95-GHz tone. Inset: zoom-in view of the electrical spectrum in a span of 2 MHz (RBW: 10 KHz).

The modulator is a dual-polarization binary phase-shift-keying (BPSK) LiNbO3 modulator (Fujitsu FTM7980EDA) which has a 3-dB bandwidth of ∼30 GHz and a half wave voltage of 3.5 V@ 21.5 GHz. After the modulator, an erbium-doped fiber amplifier (EDFA) is used to compensate for the power loss of the modulator (∼11 dB). The output optical signal is sent to a span of SMF with a length of 0.44 km. An 18 GHz PD is applied to perform electrical-to-optical conversion. To provide sufficient gain, two cascaded electrical amplifiers are applied after the PD. To extract the two RF tones, two electrical couplers (power ratio 9:1) are applied in the two loops, and the signals from the 10% port is measured. The spectral properties of the generated two-tone RF signal are analyzed by an electrical spectrum analyzer (ESA, R&S FSV40) with a phase noise measurement module.

To verify the feasibility of the proposed scheme, two electrical filters centered at 9.95 GHz and 10.66 GHz (3-dB bandwidth: 10 MHz) are applied. After stable OEO oscillation is established, a two-tone RF signal is generated. Fig 2 shows the electrical spectrum of the generated two-tone RF signal, which is clean and incorporates only the 9.95 GHz and 10.66 GHz components. Fig. 3 and Fig. 4 show the single-sideband phase noises of the 9.95 GHz tone and the 10.66 GHz tone, respectively. The insets in Fig. 3 and Fig. 4 are zoom-in views of the electrical spectrum in a span of 2MHz. The phase noise at 10 kHz frequency offset is -105.04 dBc/Hz

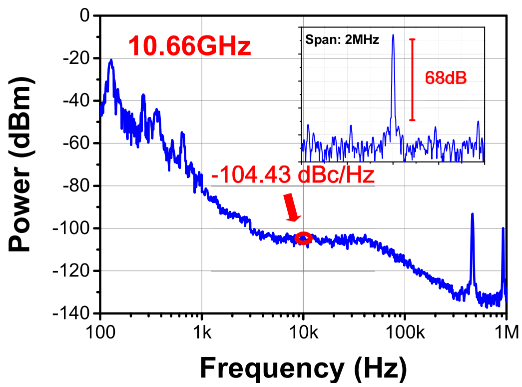

Fig. 4. Measured single-sideband phase noise of the 10.66-GHz tone. Inset: zoom-in view of the electrical spectrum in a span of 2 MHz (RBW: 10 KHz).

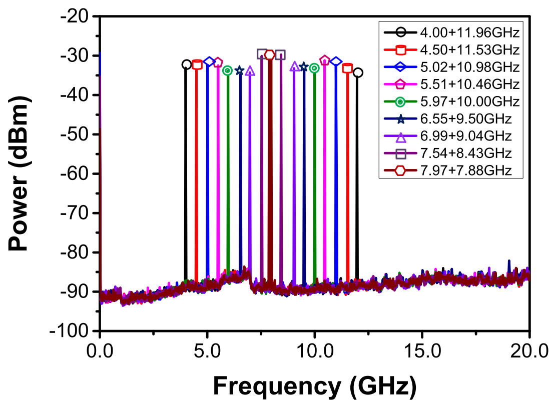

Fig. 5. Measured electrical spectra of the generated two-tone RF signals with different frequencies.

and -104.43 dBc/Hz for the two tones. Besides, the side mode spacing is about 450 kHz, and the side mode suppression ratio is greater than 65 dB. By using electrical filters with narrower bandwidth, the side modes can be further suppressed.

To demonstrate the frequency tunability, two tunable YIG filters (Watkins-Johnson WJ-621-37 & WJ-622-40) with a bandwidth of ~30 MHz are used as the TBPFs. The central frequencies of the two TBPFs can be tuned in the range of 4-8 GHz and 8-12 GHz, respectively. In the experimental demonstration, the oscillation frequencies of the two OEO loops are mainly determined by the tuning range of the two TBPFs. Fig. 5 shows the electrical spectra of the generated signals when adjusting the central frequencies of the two TBPFs with a step of 500MHz and -500MHz, respectively. The frequencies in Fig. 5 are (4.00GHz, 11.96GHz), (4.50GHz, 11.53GHz), (5.02GHz, 10.98GHz), (5.51GHz, 10.46GHz), (9.9759GHz, 10.00GHz), (6.55GHz, 9.50GHz), (6.99GHz, 9.04GHz), (7.54GHz, 8.43GHz), and (7.88GHz, 7.97GHz), where f_1 and f_2 in (f_1, f_2) are the frequencies of the two tones. The minimum frequency spacing of the two RF tones is found to be around 90 MHz, which is mainly determined by the tuning step of the TBPFs used in the experiment. By applying TBPFs with a fine tuning step, a two-tone signal with narrower frequency spacing can be generated.

In the proposed system, the use of SMF in the OEO loop may cause crosstalk between two polarization states, which would slightly affect the frequency stability and phase noise of the generated signal. This problem can be solved by using polarization maintaining fiber (PMF) in the OEO loop. In our experiment, the SMF has a very short length, thus the influence of polarization crosstalk is not obviously observed. Another problem with the proposed system is that, the nonlinearity of EA and PD would generate intermodulation components or high-order harmonics if the oscillation signal has a high power. Normally, the undesired intermodulation components or harmonics can be removed by the electrical filter. When the nonlinear frequency components are located close to the oscillation frequencies, they can be eliminated by controlling the power of the oscillating signal to ensure the devices are operating in the linear range.

IV. Conclusion

We have proposed a frequency tunable two-tone RF signal generator realized by a polarization multiplexed OEO. The proposed two-tone OEO has a simple and cost-effective structure, and the generated signal has a good quality because the optical interference and multi-frequency intermodulation due to multi-frequency oscillation are effectively suppressed. In the experiment, a two-tone RF signal with good phase noise is generated. The frequency tunability from 4 GHz to 12 GHz is demonstrated, which is only limited by the electrical devices in the experimental demonstration.

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