One-third optical frequency divider for dual-wavelength optical signals based on an optoelectronic oscillator

Hongfei Liu, Nan Zhu, Shifeng Liu, Dan Zhu✉ and Shilong Pan

An optical frequency divider for dual-wavelength optical signals based on an optoelectronic oscillator (OEO) is proposed and experimentally demonstrated. The Mach–Zehnder modulator in the OEO is biased at the minimum transmission point, the OEO-based frequency divided signal originates from system noise. When the oscillation phase and amplitude conditions met, it gets stabilised at an oscillation frequency which is one-third of the frequency interval of the injected dual-wavelength optical signal. A proof-of-concept experiment is verified. With the frequency interval of the dual-wavelength optical signal ranging from 101.4 to 120.6 GHz, the RF signals ranging from 33.8 to 40.2 GHz are successfully generated. The power ripple is lower than 2.92 dB and the rejection ratio of the harmonic components is larger than 39 dB for all the conditions. The phase noise values of the generated RF signals are kept to be around −105 dBc/Hz@10 kHz.

Introduction: The photo mixing of two highly coherent laser signals is usually used to generate microwave signals with high frequency and high quality [1, 2]. Two highly coherent laser signals can be obtained using a phase-locked loop. To make the two optical wavelengths be phase-correlated in the phase-locking loop, the frequency divider with a frequency division ratio of $1/n$ (n is an integer) is required to reduce its high frequency intervals into lower ones [3]. Traditionally, frequency dividers can be achieved using electrical techniques, but they are usually limited in working speed [1] and operation bandwidth [4]. Frequency dividers based on photonic techniques can realise the frequency division of ultra-high frequency signals with broad operation bandwidth and high working frequency [3, 5–10]. In [5], an optical frequency divider for coherent dual-wavelength optical signals is proposed using an optical frequency comb (OFC). By aligning two selected wavelengths of the OFC to the dual-wavelength optical signal using a phase-locking loop and a voltage-controlled oscillator, the optical frequency divider realises frequency division of the dual-wavelength optical signal with a frequency interval of 1.61 THz. However, the proposed system is complicated due to the requirement of the top-flat OFC and the locking of the optical comb to the dual-wavelength signal. Frequency division can also be realised utilising the non-linearities of the optical devices, such as optically injected semiconductor lasers [6], semiconductor optical amplifiers [7] and Fabry–Perot laser diodes [8] and so on. In addition, frequency division can be achieved by sub-harmonically injection-locking an optoelectronic oscillator (OEO) [9]. What is more, the half frequency division with RF signals can be realised based on an OEO without introducing RF filters in the loop [10].

In this Letter, an optical frequency divider for dual-wavelength optical signals is proposed and demonstrated based on an OEO. The dual-wavelength optical signal with a frequency interval of ω_0 is injected into the OEO loop. The Mach–Zehnder modulator (MZM) in the OEO loop is biased at the minimum transmission point (MITP). With amplitude and phase conditions met in the steady state, the oscillation frequency of the OEO would be equal to one-third of the frequency interval of the injected dual-wavelength optical signal. One-third frequency division with a dual-wavelength optical signal is achieved over a wide-frequency range with no need of high-Q EBPF in the OEO loop. A proof-of-concept experiment is carried out. With the frequency interval of the dual-wavelength optical signal tuning from 101.4 to 120.6 GHz, the RF signals ranging from 33.8 to 40.2 GHz are successfully generated. The power ripple is lower than 2.92 dB and the harmonic components rejection ratio is larger than 39 dB for all the conditions. The phase noise values of the generated RF signals are kept to be around −105 dBc/Hz@ 10 kHz.

Principle: Fig. 1 shows the schematic diagram of the proposed optical frequency divider for dual-wavelength optical signals. The dual-wavelength optical signal with a frequency interval of ω_0 is injected into an OEO loop. The OEO loop consists of an MZM biased at the MITP point, an electrical phase shifter (PS), a photodetector (PD), a wideband electrical bandpass filter (EBPF), and an electrical amplifier (EA). Assuming that the oscillation frequency of the OEO is ω_{osc}, the beat frequency of the −first-order optical sideband carried at the upper wavelength and +first-order optical sideband carried at the lower one would be $\omega_0-2\omega_{osc}$. With amplitude and phase conditions met in the steady state, the oscillation frequency would be equal to $\omega_0-2\omega_{osc}$, leading to $\omega_{osc}=1/3\omega_0$. Frequency division with the ratio of one-third for the dual-wavelength optical signal can be realised.

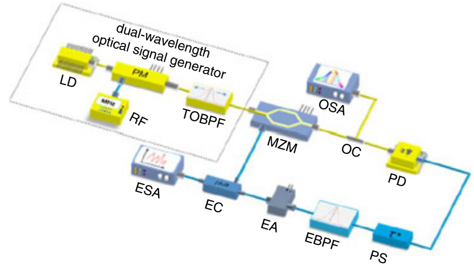

Fig. 1 *Schematic diagram of the proposed optical frequency divider for coherent dual-wavelength optical signals based on an OEO, LD: laser; PM: phase modulator; TOBPF: tunable optical filter; MZM: Mach–Zehnder modulator; OC: optical coupler; PD: photodetector; EA: electrical amplifier; PS: phase shifter; EBPF: electrical bandpass filter; EC: electrical coupler*

Mathematically, the dual-wavelength optical signal can be expressed as

$$E_{in}(t)=E_1\cos(\omega_1 t+\varphi_1)+E_2\cos(\omega_2 t+\varphi_2) \quad (1)$$

where E_1, E_2, ω_1, ω_2, φ_1 and φ_2 represent the amplitude, frequency and phase of the dual-wavelength optical signals, respectively. Supposing the oscillation signal in the OEO to be $V_{osc}(t)=V_{osc}\cos(\omega_{osc}t+\theta)$, where V_{osc}, ω_{osc}, θ represent the amplitude, frequency, phase of the signal, respectively, the output of the MZM can be expressed as

$$E_{out}(t)=E_{in}(t)\cos^2(mV_{osc}(t)+\varphi) \quad (2)$$

where φ is the offset phase of the MZM and m is the modulation depth. When the MZM is biased at the MITP point, namely $\varphi=\pi/2$, the output of the MZM could be simplified for small signal modulation as

$$E_{out}(t)=-J_1(m)\left\{\begin{array}{l}E_1[\cos(\omega_1 t+\omega_{osc}t+\varphi_1+\theta)+\cos(\omega_1 t-\omega_{osc}t+\varphi_1-\theta)]\\ +E_2[\cos(\omega_2 t+\omega_{osc}t+\varphi_2+\theta)+\cos(\omega_2 t-\omega_{osc}t+\varphi_2-\theta)]\end{array}\right\} \quad (3)$$

where $J_1(m)$ is the first-order Bessel function of the first kind. By injecting the output optical signal into the PD for optical-to-electrical conversion, the output of the PD is obtained as

$$i(t)=\alpha\eta J_1(m)^2E_1E_2\cos(\omega_2 t-\omega_1 t-2\omega_{osc}t+\varphi_2+\varphi_1-2\theta) \quad (4)$$

where α is the loss of the optical link and η is the responsivity of the PD, respectively. After passing through the EA, PS, EBPF and the electrical coupler (EC), the RF signal would be reinjected into the MZM with the expression as

$$V_{out}(t)=\alpha\eta GE_1E_2J_1(m)^2\{\cos[(\omega_2-\omega_1-2\omega_{osc})t+\varphi_2-\varphi_1-2\theta]\} \quad (5)$$

where G is the electrical gain of the EA. It should be noted that the high-order harmonics are removed by the wideband EBPF. When the oscillation of the OEO is steady, the signal $V_{osc}(t)$ should be equal to $V_{out}(t)$, which leads to

$$\begin{cases}V_{osc}=\alpha\eta GE_1E_2J_1(m)^2\\ \omega_{osc}=(\omega_2-\omega_1)/3\\ \theta=(\varphi_2-\varphi_1)/3+2k\pi\end{cases} \quad (6)$$

where k is an integer. One-third frequency division of the dual-wavelength signal can be achieved with the above conditions in (6).

Experiment: An experiment based on the setup in Fig. 1 has been performed. The key device parameters used in the experiments are as follows. The MZM (Fujitsu, FTM 7938EZ) has a 6-dB bandwidth of 41 GHz, a half-wave voltage of 4.5 V, and an extinction ratio of

26.5 dB. The EBPF has a passband of 26–41 GHz. The PD (Finisa, XPDV21 × 0) has a working bandwidth of 50 GHz and a responsivity of 0.65 A/W. Two cascaded EAs with a gain of 56 dB over a frequency range of 27–41 GHz are inserted. The electrical PS has a 40-GHz working bandwidth. A 10-dB directional EC is inserted into the OEO loop to extract part of the generated RF signal for measurement. The optical spectra and can be observed by an optical spectrum analyser (Yokogawa, AQ6370C), and the electrical spectra are observed utilising an RF signal analyser (R&S, FSWP).

In this experiment, to generate a dual-wavelength optical signal, a 26.25-GHz RF signal is modulated to the PM. By using an optical filter to select the ±second-order optical sidebands, the dual-wavelength optical signal is achieved with a frequency interval of 105 GHz (i.e. 0.84 nm), with the optical spectrum shown as the red dashed line in Fig. 2. The MZM is biased at the MITP point. When the OEO is stable, the optical output of the MZM is shown as the blue solid line in Fig. 2. The optical carrier is suppressed, being 14.2-dB lower than the ±first order optical sidebands.

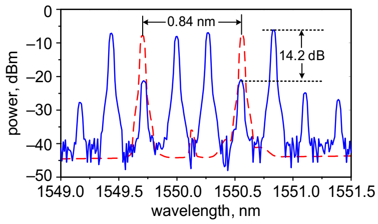

Fig. 2 *Dual-wavelength signal (red dashed line) and optical output of the MZM in the OEO loop (blue solid line)*

Figs. 3*a* and *b* show the electrical spectra and the phase noise of the generated RF signal, respectively. A 35-GHz RF signal is successfully generated, which is exactly one-third of the frequency interval of the injected dual-wavelength optical signal. It indicates the successful implementation of one-third frequency division with optical signals. The detailed electrical spectrum of the generated RF signal within a span of 200 MHz is given as the inset of Fig. 3*a*, showing a signal-to-spur ratio of 39 dB. As shown in Fig. 3*b*, the phase noise of the generated 35-GHz RF signal is 104.8 dBc/Hz @ 10 kHz.

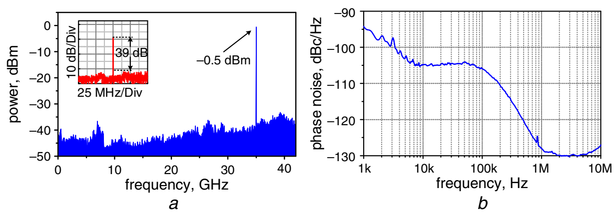

Fig. 3 *Electrical spectra and phase noise spectra*

a The electrical spectra of the generated 35-GHz RF signal
b The phase noise spectrum of the generated 35-GHz RF signal

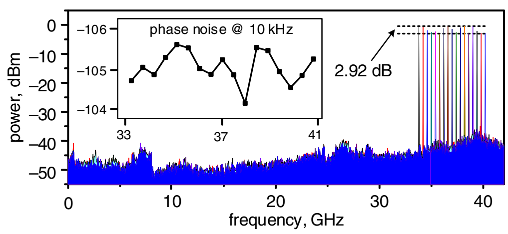

Fig. 4 *Electrical spectra of the generated RF signals ranging from 33.8 to 40.2 GHz based on the proposed frequency divider. Inset: the phase noise values @ 10 kHz for the generated RF signals*

The wideband feature is also investigated. The frequency interval of the dual-wavelength optical signal is tuned from 101.4 to 120.6 GHz with a step of 0.4 GHz. The RF signals with frequency tuning from 33.8 to 40.2 GHz are successfully generated, with the electrical spectra shown in Fig. 4. The one-third frequency division with the dual-wavelength optical signal are successfully generated for all the cases. The maximum power ripple of the generated signals is <2.92 dB. The inset of Fig. 4 shows the phase noise values at 10 kHz offset for the generated RF signals. The phase noise values are kept to be around −105 dBc/Hz@ 10 kHz for the whole frequency tuning range.

Conclusion: An optical frequency divider for dual-wavelength optical signals based on an OEO is proposed and experimentally demonstrated. The dual-wavelength optical signals with the frequency interval tuning from 101.4 to 120.6 GHz are successfully frequency divided, generating RF signals with frequency tuning from 33.8 to 40.2 GHz. The power ripple is lower than 2.92 dB, and the phase noise is kept to be around −105 dBc/Hz@ 10 kHz for the whole frequency range of 33.8–40.2 GHz. The proposed frequency divider features compact configuration, high frequency and broad operation bandwidth, which can be potentially applied to high-performance radio signal generation, clock recovery and signal processing.

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One or more of the Figures in this Letter are available in colour online.

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