Broadband two-thirds photonic microwave frequency divider

Hongzhen Zhou, Shifeng Liu, Xiaochen Kang, Nan Zhu, Kailin Lv, Yamei Zhang✉ and Shilong Pan

A broadband two-thirds frequency divider based on two cascaded carrier-suppressed double sideband (CS-DSB) modulators is proposed and experimentally demonstrated. The first CS-DSB modulator is aimed to introduce an RF signal under frequency division to the system, and the second one is employed in an optoelectronic oscillator (OEO) loop to avoid the OEO from free running. By mixing the injection frequency and the oscillation frequency in the OEO loop, oscillation of a signal with its frequency equal to two-thirds of the injection frequency is established. An experiment is carried out, RF signals with frequencies from 12.3 to 17.7 GHz are successfully divided into 8.2 to 11.8 GHz. The maximum power ripple is 2.79 dB and the harmonic components suppression ratio is larger than 36.13 dB.

Introduction: Frequency dividers play a significant role in optical communication systems and microwave photonic areas for agile frequency manipulation and signal processing [1–3]. Traditionally, frequency dividers are realised in the electrical domain with purely electronic active components [1]. Nevertheless, the active electrical components would introduce additional noise and deteriorate the signal-to-noise ratio of the systems. Also, electrical frequency dividers would also suffer from limited operational bandwidth and poor harmonic components suppression ratio. To deal with these problems, frequency dividers realised using photonic techniques are highly desired, thanks to the intrinsic characteristics brought by photonic techniques such as large bandwidth, high frequency, and electromagnetic interference immunity. Optical frequency division could be implemented based on the non-linear dynamics of a semiconductor laser [4], a non-linear fibre loop mirror [5], or an injection-locked optoelectronic oscillator (OEO) [6]. Such approaches, however, are lacking flexibility for the division of different frequencies due to the mechanism of narrowband filtering. Recently, we proposed a wideband frequency divider with a division factor of two by an OEO-based divider [7]; however, the harmonic components suppression is poor.

In this Letter, a two-thirds frequency divider with large frequency tuning range and good harmonic suppression is proposed and experimentally demonstrated based on cascaded carrier-suppressed double sideband (CS-DSB) modulations, realised by two Mach–Zehnder modulators (MZMs) biased at the minimum transmission point (MITP). When an RF signal with a frequency of f_1 is applied to the first MZM (MZM1), two sidebands that are separated by $2f_1$ would be generated, which is then sent to an OEO containing the second MZM (MZM2). Assume the frequency of the oscillation signal is f_2, at the output of MZM2 four sidebands with offset frequencies to the optical carrier of $-f_1-f_2$, $-f_1+f_2$, f_1-f_2, f_1+f_2 would be generated. To maintain the oscillation of the OEO, the beating frequencies of $-f_1+f_2$ and f_1-f_2 should equal to f_2, leading to $f_2=2/3f_1$. As a result, two-thirds frequency division can be realised. With a wideband bandpass filter (BPF) inserted in the OEO, frequency division over a wide-frequency range can be realised, and the harmonic interferences can be effectively removed. Besides, the interference of the free-running signal is also suppressed, thanks to the CS-DSB modulation, which would further improve the harmonic suppression performance.

Principle: Fig. 1 shows the schematic diagram of the proposed two-thirds frequency divider, which consists of a laser source (LS), two MZMs, an erbium-doped fibre amplifier (EDFA), a photodetector (PD), an RF amplifier, a phase shifter, a wideband BPF, and a power splitter. A lightwave from the LS is modulated by a microwave signal to be converted at the MZM1, which is biased at the MITP by adjusting the DC bias, and a CS-DSB modulated signal is generated. The CS-DSB modulated signal is then directed into the OEO through the MZM2, which operates at the MITP as well. By beating the optically modulated sidebands in the PD, an intermediated frequency (IF) signal with a frequency equal to the difference between the doubled injection frequency and the doubled oscillation frequency is generated. The IF signal is amplified and re-injected into MZM2 to form the oscillation. To maintain the oscillation, the frequency of the IF must be the two-thirds frequency of the injection signal. As a result, a two-thirds frequency divider is realised.

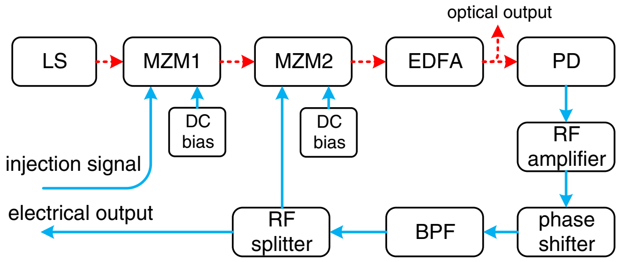

Fig. 1 *Schematic diagram of two-thirds frequency divider based on OEO, LS: laser source; MZM: Mach–Zehnder modulator; EDFA: erbium-doped fibre amplifier; PD: photodetector; BPF: bandpass filter*

Mathematically, supposing that the expressions of the injection RF signal to MZM1 and the oscillation signal in the OEO are $V_{in}(t)=V_0\cos(\omega_0 t+\theta_0)$ and $V_{osc}(t)=V_1\cos(\omega_1 t+\theta_1)$, respectively, where ω_i, V_i, θ_i, $(i=0,\ 1)$ represent the angular frequency, the amplitude, and the phase of the two signals, the outputs of MZM1 and MZM2 are expressed as

$$P_{MZM1}(t)=P_{in}\sin^2\left(\frac{\pi V_{in}(t)}{2V_{\pi 0}}+\varphi_{b0}\right) \quad (1)$$

$$P_{MZM2}(t)=P_{MZM1}\sin^2\left(\frac{\pi V_{osc}(t)}{2V_{\pi 1}}+\varphi_{b1}\right) \quad (2)$$

where P_{in} is the power of the optical carrier from the LS, $V_{\pi i}$, φ_{bi}, $(i=0,\ 1)$ are the half-wave voltages and the bias phase of MZM1 and MZM2, respectively. By biasing MZM1 and MZM2 at the MITP, i.e. $\varphi_{b1}=\varphi_{b2}=0$, the output optical signal at MZM2 becomes

$$P_{MZM2}(t)=P_{in}\sin^2\left(\frac{\pi V_{in}(t)}{2V_{\pi 0}}\right)\sin^2\left(\frac{\pi V_{osc}(t)}{2V_{\pi 1}}\right) \quad (3)$$

The signal in (3) is then converted into the electrical domain by the PD, and the output current can be written as

$$\begin{aligned} i(t)=\frac{\eta P_{in}\alpha}{4}\{1-\cos[\beta_1\cos(\omega_1 t+\varphi_1)]-\cos[\beta_0\cos(\omega_0 t+\varphi_0)] \\ +\cos[\beta_1\cos(\omega_1 t+\varphi_1)]\cos[\beta_0\cos(\omega_0 t+\varphi_0)]\} \end{aligned} \quad (4)$$

where α and η are the attenuations of the optical link and the responsivity of the PD, $\beta_i=\pi V_i/V_{\pi i}$ $(i=0,\ 1)$ are the modulation indices of MZM1 and MZM2, $\varphi_i=\theta_i-\omega_i\tau$ $(i=0,\ 1)$, and τ is the time delay introduced by the oscillation loop. The electrical signal goes through the RF amplifier, the phase shifter, and the BPF, and is then applied back to the RF port of MZM2, which can be given by

$$V_{out}(t)=\frac{\eta P_{in}\alpha G}{2}J_2(\beta_0)J_2(\beta_1)\cos[2(\omega_0-\omega_1)t+2(\varphi_0-\varphi_1)] \quad (5)$$

where J_n is the nth-order Bessel function of the first kind and G is the gain of the electrical components. For steady state, the signal $V_{out}(t)$ should be equal to $V_{osc}(t)$, so the frequency of the output signal ω_1 should equal to $2\omega_0/3$, and the following conditions must be satisfied:

$$\begin{cases} V_1=\eta P_{in}\alpha G J_2(\beta_0)\cdot J_2(\beta_1)/2 \\ 3\theta_1=2\theta_0-2\omega_0\tau/3+2k\pi \end{cases} \quad (6)$$

where k can be an arbitrary integer.

Experiment: An experiment based on the setup in Fig. 1 is carried out. The parameters of the key devices used in the experiment are listed as follows. The wavelength and the power of the LS (Teraxion, PS-NLL) are 1550.52 nm and 15.35 dBm, respectively. The 3 dB bandwidth, the half-wave voltage, and the extinction ratio of the two MZMs (Fujitsu, FTM 7938EZ) are 33.9 GHz, 4.5 V, and 26.5 dB, respectively. The PD has a bandwidth of 50 GHz and a responsivity of 0.65 A/W. The output signal of the PD is amplified by the RF amplifier ranging from 2 to 18 GHz with a gain of 52 dB. The frequency ranges of the phase shifter, the BPF, and the power splitters are from DC to 40, 8 to 12, and 2 to 18 GHz, respectively. The electrical spectra are observed by a phase noise analyser with spectrum measurement module (R&S, FSWP), and the optical spectra are measured by an optical spectrum analyser (Yokogawa, AQ6370C).

Fig. 2 shows the optical spectra measured at the output of MZM2. The frequency of the injection RF signal is 14.7 GHz. When the OEO loop is open, only the ±1st-order optical sidebands are observed, as shown in Fig. 2*a*. The optical carrier is 20 dB lower than the ±1st-order optical sidebands, indicating that CS-DSB modulation is successfully realised by MZM1. When the OEO loop is closed, four main sidebands are observed as illustrated in Fig. 2*b*. The sideband-to-carrier suppression ratio is 12.9 dB, indicating that CS-ODSB modulation is also realised at MZM2.

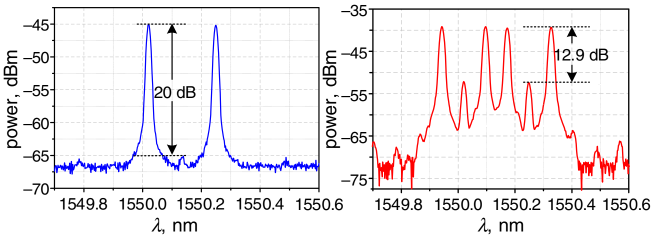

Fig. 2 *Optical spectra at output of MZM2 in different cases*

a Output with OEO loop open
b Output with OEO loop closed

The signal from Fig. 2*b* is then applied to the PD to perform the optical to electrical conversion, and the BPF ranging from 8 to 12 GHz is employed to remove the harmonic components. Fig. 3*a* shows the output electrical spectra of the BPF. As shown as the red curve in Fig. 3*a*, a signal with a frequency of 9.8 GHz is successfully generated, which is exactly two-thirds the frequency of the 14.7 GHz injection signal, indicating that two-thirds frequency division is successfully realised. If no signal is injected to MZM1, there would be no signal generated from the system, as shown as the blue curve in Fig. 3*a*. The phase noise spectra of the 9.8 GHz frequency-divided signal and the 14.7 GHz injection signal are measured, with the results shown in Fig. 3*b*. The phase noises of the two signals at the 10 kHz offset are −112.38 and −115.65 dB/Hz, and there is 3.27 dB improvement in the phase noise performance, which fits well with the theoretical value 3.52 dB.

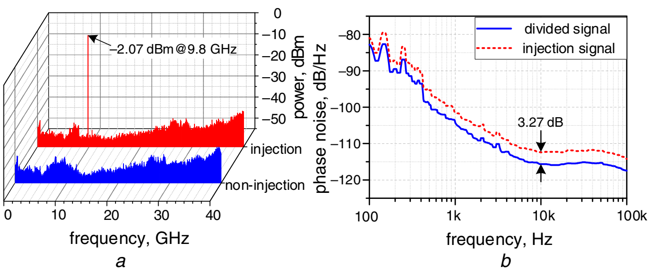

Fig. 3 *Electrical spectra and phase noise spectra*

a Output electrical spectra of divider with and without 14.7 GHz injection signal
b Phase noise spectra of 14.7 GHz injection signal and 9.8 GHz frequency-divided signal

The wideband feature of the proposed frequency divider is also investigated by changing the injection frequency from 12.3 to 17.7 GHz with a frequency step of 0.6 GHz. As shown in Fig. 4, 8.2 to 11.8 GHz frequency-divided signals are successfully generated by the proposed scheme. The maximum power ripple of the frequency-divided signal at different frequencies is less than 2.79 dB, which is mainly due to the uneven frequency response of the electrical devices. Thanks to the BPF, the harmonic components are effectively removed, which are more than 36.13 dB lower than the wanted components, showing that the system has a good harmonic suppression performance.

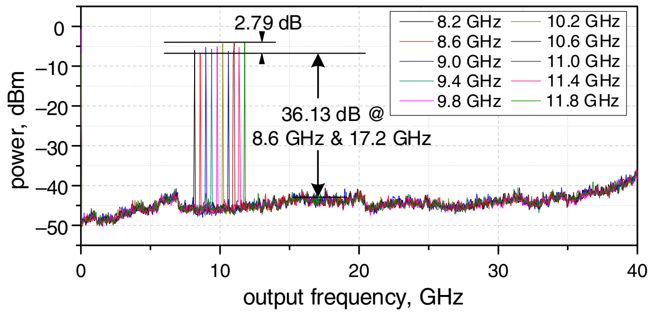

Fig. 4 *Electrical spectra of divided frequencies from 8.2 to 11.8 GHz with maximum power ripple of 2.79 dB*

Conclusion: A broadband two-thirds frequency divider based on cascaded CS-DSB modulation is proposed and experimentally demonstrated. RF signals with frequencies from 12.3 to 17.7 GHz are successfully divided into 8.2–11.8 GHz, and the maximum power ripple is smaller than 2.79 dB. The phase noise of the frequency-divided signal at the 10 kHz offset was 3.27 dB lower than the injection signal, which fits well with the theoretical value. The harmonic suppression ratio is larger than 36.13 dB. The proposed frequency divider features large operation bandwidth and good harmonic suppression, which is highly desired in optical communications, microwave signal processing, and microwave signal synthesis.

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

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