Tunable multi-frequency optoelectronic oscillator based on a microwave photonic filter and an electrical filter

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Abstract
We propose and experimentally demonstrate a multi-frequency optoelectronic oscillator (OEO) based on the phase-modulation to intensity-modulation conversion. A microwave photonic filter incorporating an optical fiber Bragg grating Fabry–Perot filter and an electrical yttrium iron garnet (YIG) filter in two branches are used to select the oscillation modes of the OEO. By adjusting the wavelength of laser source or the central frequency of YIG filter, two frequencies can be tuned independently within a wide range. The single sideband phase noises of the generated frequencies are measured experimentally. Moreover, the OEO shows potential ability to achieve more frequencies oscillation by multiplexing more optical and electrical filters.

Keywords Microwave generation · Microwave photonics · Optoelectronic devices

1 Introduction
Microwave photonics studies the interaction between microwave and optical signal, whose major functions include photonic generation of microwave signals (Neyer and Voges 1982; Berceli and Herczfeld 2010), photonic processing of microwave signals (Tsuchida and Suzuki 2005; Pan and Yao 2009, 2010), optically controlled phased array antennas, and photonic analog-to-digital conversion (Yao 2009). With the fast development of information industry in recent years, there has been a pressing need for high-frequency signal sources with wideband tunability in a lot of fields such as channelized digital receiver, next generation wireless radio communication (Li et al. 2016) and modern radar (Ghelfi et al. 2014; Wang et al. 2018). Optoelectronic oscillator (OEO) is a promising method to generate microwave signals with high-frequency, high-stability, and high spectral-purity
(Yao and Maleki 1996). A trend in wireless applications has been developing multi-mode and multi-band operation, particularly for automotive radar applications (Jain et al. 2009). However, traditional OEO can only generate one single frequency. Although multi-frequency could be achieved by employing more than one OEO, it will increase cost and complexity of the system, and the coherence of frequencies cannot be guaranteed. Meanwhile, the oscillation frequency is usually fixed, which is determined by weak tunability of the filter.

To solve this problem, many researchers have carried out their works in order to generate more than one frequency simultaneously in terms of the OEO. Jiang et al. demonstrated a dual-frequency OEO by simply adding two electrical filters in parallel branches (Jiang et al. 2014). However, because of the use of fixed electrical filters, the generated signals were not tunable. Kong et al. employed a polarization modulator (PolM) and a phase-shifted fiber Bragg grating (PS-FBG) to form a dual-frequency OEO (Kong et al. 2013). When transverse force was applied, two orthogonally polarized notches of the PS-FBG will be changed because of fiber birefringence, as well as the oscillation frequencies. However, the tunability of the two frequencies are not independent. A tunable multi-frequency OEO based on stimulated Brillouin scattering was reported by Zhou et al. (2015). This scheme used stimulated Brillouin scattering (SBS) effect to convert phase-modulation into intensity-modulation, and independently tuning of each generated frequency can be achieved by changing the wavelength of the corresponding tunable laser source. Xie et al. (2016) used a dual-parallel Mach–Zehnder modulator (DPMZM) to form a dual-frequency OEO with low intermodulation. Independent tunability is achieved by using two parallel electrical filters.

In this letter, we proposed and experimentally demonstrated a multi-frequency OEO scheme based on the phase-modulation to intensity-modulation (PM-IM) conversion (Li and Yao 2012). The OEO is composed of two filtering branches. One branch employs a microwave photonic filter (MPF) including a tunable laser source (TLS), a phase modulator (PM) a fiber Bragg grating Fabry–Perot (FBG-FP) filter and a photodetector (PD) to achieve PM-IM conversion and select one oscillation frequency. By tuning the wavelength of the TLS, the oscillation frequency tunability can be achieved. The other branch also incorporates the PM-IM conversion, in which a section of single mode fiber (SMF) is used as dispersive device to convert phased modulated optical signal to intensity modulated signal. The oscillation mode is then selected using an electrical yttrium iron garnet (YIG) filter, which can be tuned by changing the driving voltage of the YIG filter. Experiments are carried out to demonstrate the feasibility and tunability of our approach. The phase noise performance of two generated signals is also investigated.

2 Principle of operation

The configuration diagram of proposed OEO is illustrated in Fig. 1. The OEO consists of a TLS, a PM, an optical coupler (OC), an optical circulator, an FBG-FP filter, an erbium-doped fiber amplifier (EDFA), two PDs, a section of SMF, a variable optical attenuator (VOA), an electric coupler (EC) and a microwave power amplifier (PA). A continuous wave (CW) light from the TLS is sent to the PM. The phase modulated light signal is divided into two branches by a 1:1 OC. The two branches use optical and electrical filtering methods to filter out two different electrical signals, respectively. Then
the signals are combined by an EC and amplified by a PA. Finally, the signals are sent back to the PM to make the oscillation loop closed.

In order to achieve independent tunability, an optical filtering branch and an electrical filtering branch are used to select and tune two different oscillation frequencies. The upper branch in Fig. 1 uses the MPF that consists of the TLS, PM, FBG-FP and PD to determine an oscillation frequency. The operating principle of this MPF is shown in Fig. 2, where the black line refers to the optical carrier. Figure 2a, b depict the phase modulated signal before and after the FBG-FP, respectively. Assuming the reflection top of FBG-FP is flat, the signal at the output of PD1 is given by Li et al. (2012)

**Fig. 1** Schematic diagram of the proposed tunable multi-frequency OEO

**Fig. 2** Operation principle of the optical filtering branch. a The phase-modulated signal. b The phase-modulated signal after filtered by the FBG-FP
where $r(\cdot)$ is the power reflection coefficient of the FBG-FP, $\omega_e$ is the angular frequency of the modulating signal, $\omega_o$ is the angular frequency of the light wave. $J_n(\cdot)$ is the nth-order Bessel function of the first kind. $E_o$ is the amplitude of the incident light wave. When no first-order sidebands fall into the notch of the FBG-FP filter, we have
\[
\sqrt{r(\omega_0 + \omega_e)} = \sqrt{r(\omega_0 - \omega_e)}
\]
(2)
\[
\theta_1 = \theta_2
\]
(3)
According to Eq. (1), no signal will be detected (like the red sideband in Fig. 2). However, when the notch of FBG-FP filters out one sideband of desired signal (like the blue sideband in Fig. 2), the Eqs. (2) and (3) will not be satisfied. Thus, phase-modulated signal is converted to intensity-modulated signal. A signal is detected by the PD, whose frequency is equal to the difference between the notch of the FBG-FP filter and the wavelength of optical carrier. In this case, tunability can be easily realized by tuning the wavelength of the TLS.

On the other hand, the PM-IM conversion in the lower filtering branch is achieved by using a dispersive device. The operation process of the lower filter branch is shown in Fig. 3.

It has been demonstrated that the combination of a TLS, a PM, a section of SMF, and a PD form an MPF whose frequency response is shown as the blue line in Fig. 3a (Zeng and Yao 2005). The optical field after the SMF can be expressed as
\[
E(t) \propto J_0 \cos (\omega_0 t + \phi_0)
+ J_1 \cos \left( \omega_1 t + \frac{\pi}{2} + \phi_1 \right)
- J_1 \cos \left( \omega_2 t - \frac{\pi}{2} + \phi_2 \right)
\]
(4)
where $\varphi_0$, $\varphi_1$, and $\varphi_2$ are the phase delays of the spectral components $\omega_0$, $\omega_1$, and $\omega_2$ induced by the chromatic dispersion of the SMF, respectively. The chromatic dispersion of the SMF induces different phase delays for different sidebands, changing the phase modulated signal into intensity modulated signal. Finally, the recovered RF signal can be expressed as

$$E_{RF}(t) \propto \cos \left( \frac{\pi \chi \lambda_0^2 f_m^2}{c} + \frac{\pi}{2} \right) \cdot \cos \left( \omega_m t + \theta \right)$$

where $\chi$ is the accumulated dispersion of SMF, $\lambda_0$ is the wavelength of optical carrier, $f_m$ is the frequency of the modulating signal, $c$ is the velocity of light in vacuum, $\theta$ is the phase delay of the recovered signal. It can be seen from Eq. (5), the first notch locates at the dc frequency. The second notch is determined by

$$\pi \chi \lambda_0^2 f_m^2 / c = \pi$$

As can be seen, we can obtain a rather wide passband up to tens of gigahertz by choosing the SMF with proper length. This passband is wide enough to cover the oscillation turning range. Since the value of optical carrier wavelength is much smaller than the value of modulating signal, the wavelength change of the optical carrier will cause little impact on the passband, according to Eq. (6). In other words, the tuning of the upper filtering branch is independent on the lower one. To realize a narrow band filtering branch, an electrical YIG filter is employed to select the oscillation frequency. The YIG filter is a band-pass filter with a bandwidth as narrow as tens of megahertz and a large tunability up to tens of gigahertz.

The frequency response of the YIG filter is shown as the red line in Fig. 3a. Figure 3b shows the frequency response of the whole lower filtering branch. By adjusting the driving voltage of the YIG filter, the passband can be continuously tuned within a wide range.

3 Experiment results and discussion

An experimental investigation is carried out according to the setup shown in Fig. 1. A TLS with a maximum output power of 16 dBm is used as the light source. The bandwidth of the PM is larger than 30 GHz. The FBG-FP fiber filter has a reflection bandwidth of about 0.7 nm and is composed of two wavelength matched Bragg gratings with appropriate separation. The cavity length of the FBG-FP filter is several millimeters so as to achieve a single notch within the reflection band. The notch wavelength of the FBG-FP locates at 1551.168 nm with a 3 dB bandwidth of 90 MHz. The SMFs used in the optical and electrical branch are 400 m and 4000 m, respectively. Two PDs with the bandwidth up to 50 GHz are used for photoelectric conversion. A VOA at the input of the PD is inserted to make the gain of this filtering branch at the same magnitude with the other one. The central frequency of the YIG filter can be tuned by controlling its driving voltage from 0 to 10 V.

Before investigating the oscillation characteristics of the OEO, the open loop frequency response is measured through a vector network analyzer (VNA, Keysight N5244A). Figure 4a shows the measured frequency response with the TLS wavelength of 1551.26 nm and the YIG driving voltage of 6.2 V. Two frequency peaks locate at 11.58 GHz and 25.52 GHz can be observed. The 3 dB bandwidths of the two peaks are 90 MHz and 24 MHz, respectively.
Then, the OEO loop is closed. Once the EDFA and the VOA are tuned at proper values, two frequencies will oscillate simultaneously, as shown in Fig. 4b. The generated signals are monitored by an electrical spectrum analyzer (ESA, Keysight N9040B). Mode competition exists in the cavity since both frequencies share the same electrical amplifier. However, when the frequency difference of the two oscillating signals is large enough, two stable oscillating signals can be observed by controlling the optical and electrical gain of the OEO loop. Only beat frequency and second-order harmonic signal exist, which can be suppressed to more than 20 dB lower than the oscillating signals, as shown in the Fig. 4b. Figure 5 shows the zoomed-in view of the two oscillating signals when the two oscillating frequencies are tuned around 14.99 GHz and 25.66 GHz, respectively. Figure 5a depicts the oscillating frequency for the optical branch, in which the mode spacing can be calculated to be 429.31 kHz. A sidemode suppression ratio (SMSR) of 43.37 dB can be observed. Other spurs can also be observed, which are caused by the modes of the electrical branch.

![Fig. 4](image)

**Fig. 4**  a The frequency response of the dual-frequency MPF; b the electrical spectrum of oscillation signals

![Fig. 5](image)

**Fig. 5**  a Zoomed-in view of the oscillating frequency of the optical branch with a span of 10 MHz; b zoomed-in view of the oscillating frequency of the electrical branch with a span of 600 kHz
Similarly, the mode spacing and the SMSR of the electrical branch are 49.56 kHz and 53.12 dB, respectively. The SMSR of the optical branch is not as high as that of the electrical branch because of the relatively large bandwidth of the MPF. The SMSR performance of the optical branch can be much improved by employing an FBG-FP with narrower notch bandwidth.

To prove the independent tunability of two frequencies, we measured the tunability of one frequency by keeping the other unchanged. First, we fixed the driving voltage of YIG filter at 6.2 V and increased the wavelength of the TLS from 1551.20 to 1551.29 nm. The electrical spectrum in Fig. 6a shows that the oscillation frequency of signal 1 increases from 5.81 to 18.18 GHz, while the frequency of signal 2 keeps stable. The tunning range of signal 1 is limited by the reflection bandwidth and the notch position of the FBG-FP filter. To improve the tuning range, FBG-FP filter with broader reflection bandwidth can be used. Figure 6b demonstrates the linear relationship between the frequency of signal 1 and the wavelength of the TLS. Since the wavelength tuning resolution of the TLS is 1 pm, the frequency tuning resolution of the signal generated by the optical branch should be 125 MHz. Furthermore, more PS-FBGs with different central wavelengths can be cascaded to achieve multi-frequency oscillation for the optical branch when a multi-wavelength laser source is used.

Then the wavelength of TLS is fixed at 1551.26 nm, and the driving voltage of the YIG filter is increased from 2.9 to 5.9 V in order to demonstrate the electrical tunability. The frequency tuning resolution of the YIG filter is about 50 MHz. Figure 7a shows the superimposed spectra of the proposed OEO. As depicted in Fig. 7a, the signal 1 keep unchanged at 11.91 GHz when signal 2 is tuned over a range from 13.11 to 24.31 GHz. The relationship between the frequency of signal 2 and the driving voltage of the YIG filter is shown.

![Fig. 6 a The superimposed spectra of the generated signals under different TLS wavelengths; b the relationship between the frequency of signal 1 and the TLS wavelength](image)
in Fig. 7b. The strong spurs in Fig. 6 are the beat signals and harmonic signals, which are mainly caused by the nonlinearity of the phase modulation and the electrical devices such as amplifiers. To suppress these spurs, other modulators such as polarization modulator (PolM) or polarization division multiplexing dual parallel MZM (PDM-MZM) can be used, to which the two oscillating frequencies can be separately applied. To achieve multi-frequency oscillation for the electrical branch, more electrical BPFs with different frequencies can be paralleled.

The stability of oscillation frequency is also investigated experimentally by measuring the single sideband (SSB) phase noise. The two frequencies of the OEO are set at 6.60 GHz and 22.38 GHz. Figure 8a, b shows that the phase noise of signal 1 and signal 2 at 10 kHz are $-97.38$ dBc/Hz and $-112.13$ dBc/Hz, respectively. Some spurs that correspond to the mode spacing and intermodulation could be observed. Since short fiber length is adopted in the optical branch, the SSB phase noise performance is not well enough. This could be improved by adding multi-loop structure with long fiber length. Meanwhile, the MPF and BPF with narrower passband can be used to improve the stability of the generated signal.
Conclusion

We proposed and experimentally demonstrated a tunable multi-frequency OEO based on an MPF and an electrical filter using the PM-IM conversion. The oscillation frequencies were determined by the MPF and the electrical YIG filter. Two oscillating frequencies were generated, and independent tunability was achieved simply by changing the wavelength of the TLS or the passband of the YIG filter. By multiplexing more optical and electrical filters, the proposed OEO was capable of supporting more oscillating frequencies. The experimental results demonstrated the feasibility and tunability of the proposed OEO, showing the potential application of the OEO in the field of multi-mode and multi-band systems, particularly for automotive radar applications.

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Declaration

Conflict of interest The authors declare that there are no conflicts of interest related to this article.

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