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# Weak RF signal detection with high resolution and no blind zone based on ultra-simple multi-mode optoelectronic oscillation

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Weak RF signal detection with high resolution and no blind zone based on directly modulated multi-mode optoelectronic oscillation has been proposed. The high-sensitivity optical modulators and optical filters are avoided because multi-mode oscillation is obtained based on directly modulating the semiconductor laser at the relaxation oscillation frequency. For the directly modulated optoelectronic oscillator, the detection characteristics such as gain for the RF signal, resolution, noise floor, and sensitivity are firstly analyzed. The experimental results are consistent with the simulated results. For the RF signal of unknown frequency, it can be detected out and amplified by tuning the bias current and delay time of the loop. There is no blind zone within 1–4.5 GHz. The system provides a maximum gain of 17.88 dB for the low-power RF signal. The sensitivity of the system can reach as high as −95 dBm. The properties such as gain dynamic range and power stability are also investigated. The system has potential for weak RF signal detection, especially for the RF signal with unknown frequency.

**Keywords:** radio frequency detection; optoelectronic oscillator; distributed feedback semiconductor laser.

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## 1. Introduction

Low-power radio frequency (RF) signal detection plays an important role in many applications[1–5]. In the traditional electrical domain, many methods have been proposed and applied to detect the weak RF signal[6]. However, in these systems, the sensitivity is not high enough. The multi-mode optoelectronic oscillator (OEO) is demonstrated to be applied in detecting weak RF signal with high sensitivity[7–10]. In Ref. [7], the RF signal from 1 to 6 GHz with the sensitivity as low as −83 dBm can be detected based on the multi-mode OEO. However, the gain for the signal reduces from 3 GHz, and the mode spacing is 5.2 MHz. Based on a phase-shifted fiber Bragg grating, Shao *et al*. realized RF signal detection with the gain of about 10 dB from 1.5 to 5 GHz[8]. However, the mode spacing of the system is 4.7 MHz. The mode spacing is improved to 450 kHz based on the highly nonlinear fiber[9]. However, the above systems based on the external modulator need a high-sensitivity modulator to make sure the weak RF signal can be injected to the system. The ultra-simple detection system based on direct modulation OEO is realized in Ref. [10]. However, owing to the inherent characteristics of multi-mode oscillation, the RF signal that mismatches the oscillation modes cannot be detected. The ability to search and determine the unknown signal's frequency is significant.

In this paper, an ultra-simple method of weak RF signal detection with high resolution and no blind zone is proposed based on the multi-mode OEO. The OEO is realized utilizing the high modulation efficiency at the relaxation oscillation peak of the distributed feedback (DFB) semiconductor laser, which avoids using the optical modulator with high sensitivity. The characteristics such as gain for RF signal, resolution, noise floor, and sensitivity of the system based on the directly modulated multi-mode OEO are firstly analyzed. The resolution of the system is as high as 180 kHz. The unknown weak RF signal can be determined by adjusting the bias current and the optical tunable delay line (OTDL) to make the oscillation modes match with the RF signal. So, there is no blind zone within 1–4.5 GHz. The maximum gain provided for the signal is 17.88 dB, the sensitivity reaches up to −95 dBm, and the gain dynamic range is 84.5 dB. The system is stable, which indicates that the simple system can be applied to satellite phones.

## 2. Principle and Experimental Setup

The RF detection system is set up according to the structure shown in Fig. 1. The optical signal is generated from a DFB semiconductor laser. It is amplified by the erbium-doped fiber amplifier (EDFA), which provides gain to compensate the loop loss. After transmitting through the 1.1 km single mode fiber (SMF), the optical carrier is sent to the OTDL (KG-ODL-15-PMF-10) with the max delay time of 400 ps, which is used to adjust the optical path length. The optical signal converts to electrical signal on the photodetector (PD, responsivity: 0.85 A/W). Then, the electrical signal will be sent to the RF port of the laser through the 5:5 electrical splitter (ES) and 5:5 electrical coupler (EC) to directly modulate the DFB laser. Thus, the optoelectronic oscillation loop is formed. The RF signal generated by the microwave signal generator is injected to the system through the ES. The output RF signal is monitored by the electrical signal analyzer (ESA).

Thanks to the directly modulated OEO, the RF signal located at relaxation oscillation frequency $f_m$ will achieve the highest modulation efficiency when a semiconductor laser is directly modulated[11]. It can be clearly seen from the frequency response of the semiconductor laser in Fig. 2(a). The current of the RF signal can be expressed as

$$I_{\mathrm{RFin}}(t) = I_{\mathrm{RF}} \cos 2\pi f_m t, \tag{1}$$

where $I_{\mathrm{RF}}$ is the amplitude of the RF current. The directly modulated optical signal generated from the DFB laser has three frequency components: $f_c$, $f_c + f_m$, and $f_c - f_m$, as shown in Fig. 2(b). For direct modulation, the output optical power can be expressed as

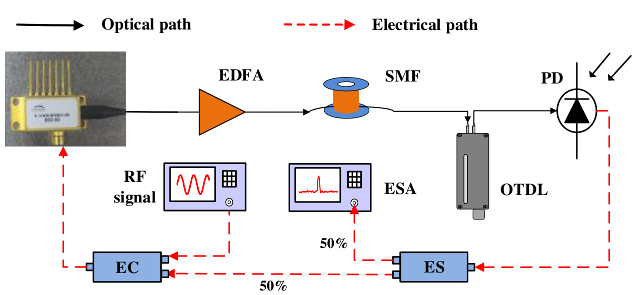


**Fig. 1.** Schematic diagram of the proposed RF signal detection (EDFA, erbium-doped fiber amplifier; SMF, single mode fiber; OTDL, optical tunable delay line; PD, photodetector; EC, electrical coupler; ES, electrical splitter; ESA, electrical spectrum analyzer).

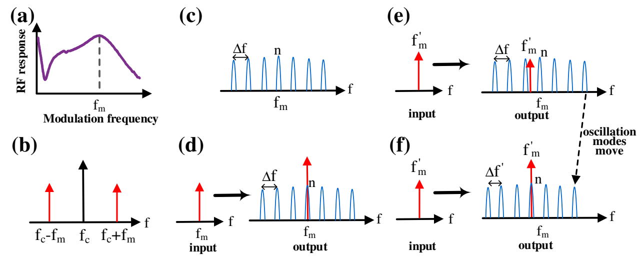


**Fig. 2.** Illustration of the RF signal detection. (a) Modulation response of the laser with a relaxation oscillation at $f_m$. (b) Optical signal from the DFB laser after modulation. (c) Multi-mode oscillation state around $f_m$ after closing the loop when there is no input RF signal. (d) The RF signal $f_m$ is amplified when it matches with the oscillation mode. (e) The RF signal $f_m'$ has loss when it mismatches with the oscillation mode. (f) The RF signal $f_m'$ is amplified after tuning the delay time of the OTDL.

$$\begin{aligned} P(t) &= S_{\mathrm{LD}}(I_{\mathrm{bias}} - I_{\mathrm{th}} + I_{\mathrm{RFin}}) \\ &= P_{\mathrm{bias}} + S_{\mathrm{LD}} I_{\mathrm{RF}} \cos 2\pi f_m t, \end{aligned} \tag{2}$$

where $S_{\mathrm{LD}}$ is the slope efficiency of the DFB laser with 0.3 W/A, $I_{\mathrm{bias}}$ is the DC bias current, $I_{\mathrm{th}}$ is the threshold current of the laser, and $P_{\mathrm{bias}}$ is the optical power at the DC bias current. The output signal is amplified by the EDFA and transmitted through the SMF, which can be written as

$$\begin{aligned} P'(t) &= S_{\mathrm{LD}} \alpha G_{\mathrm{EDFA}}(I_{\mathrm{bias}} - I_{\mathrm{th}} + I_{\mathrm{RFin}}) \\ &= \alpha G_{\mathrm{EDFA}} P_{\mathrm{bias}} + S_{\mathrm{LD}} \alpha G_{\mathrm{EDFA}} I_{\mathrm{RF}} \cos 2\pi f_m t, \end{aligned} \tag{3}$$

where $\alpha$ (0.3 dB) is the loss of the SMF and OTDL, and $G_{\mathrm{EDFA}}$ is the gain of the EDFA. Through photoelectric conversion, the photogenerated current can be expressed as

$$\begin{aligned} I_{\mathrm{PD}}(t) &= r_{\mathrm{PD}} P'(t) \\ &= r_{\mathrm{PD}} \alpha G_{\mathrm{EDFA}} P_{\mathrm{bias}} + r_{\mathrm{PD}} S_{\mathrm{LD}} \alpha G_{\mathrm{EDFA}} I_{\mathrm{RF}} \cos 2\pi f_m t, \end{aligned} \tag{4}$$

where $r_{\mathrm{PD}}$ is the photoelectric conversion efficiency of the PD with 0.85 A/W. The latter term in Eq. (4) is the output RF signal current. So, the output RF power at the PD can be expressed as

$$P_{\mathrm{PDRF}} = (r_{\mathrm{PD}} S_{\mathrm{LD}} \alpha G_{\mathrm{EDFA}})^2 P_{\mathrm{RFin}}. \tag{5}$$

The open loop gain is obtained in Eq. (6), which is proportional to $r_{\mathrm{PD}}$, $S_{\mathrm{LD}}$, and $G_{\mathrm{EDFA}}$:

$$G_{\mathrm{open}} = (r_{\mathrm{PD}} S_{\mathrm{LD}} \alpha G_{\mathrm{EDFA}})^2. \tag{6}$$

The single mode RF signal can be obtained by directly modulating the DFB laser based on OEO as long as the open loop gain is high enough[11]. For the RF signal detection, the open loop gain is just below the threshold gain of single mode oscillation. By adjusting the pump current of the EDFA to decrease the open loop gain, multiple modes will oscillate in the loop, as shown in Fig. 2(c). The mode spacing $\Delta f$ is determined by the loop length[12]. So, the number of the oscillation mode at $f_m$ is $n = f_m/\Delta f$. Accordingly, the RF signal with $f_m$ will acquire the maximum gain in Fig. 2(d). However, the RF signal located at $f'_m$, which mismatches with the oscillation modes, will show loss, as in Fig. 2(e). Here, the resolution of the system is defined as the minimum frequency difference when the RF signal can obtain maximum gain, which is equal to mode spacing. Hence, the resolution can be improved by increasing the loop length. Then, adjusting the delay time $\Delta\tau$ of OTDL to change the loop length, the mode spacing will be changed to $\Delta f'_m$, and the frequency of the $n$th oscillation mode will be tuned to $f'_m = n \times \Delta f'_m$. The RF signal will rematch with the $n$th mode and get amplified correspondingly, as shown in Fig. 2(f). The relationship between the delay time $\Delta\tau$ and mode spacing can be expressed as $\Delta f'_m = \Delta f_m/(1 + \Delta\tau\,\Delta f_m)$. When the cover range of the $n$th mode reaches the resolution, i.e., $n(\Delta f_m - \Delta f'_m) = \Delta f_m$, the required $\Delta\tau$ can be expressed as

$$\Delta\tau = 1/(f_m - \Delta f_m). \tag{7}$$

So, the system can realize the RF signal detection without a blind zone within the detection bandwidth.

### 2.1. Gain property of the detection system

In the OEO loop, the total field is the summation of all circulating fields[12,13]. For the input RF signal $I_{\mathrm{RFin}}(\omega)$, $\omega$ is angular frequency, and the current of the signal injected to the DFB laser can be expressed as

$$\begin{aligned} I_{\mathrm{out}}(\omega,t) &= I_{\mathrm{in}}(\omega)G(I_0)\sum_{n=0}^{\infty} G(I_0)\exp[i\omega(t - n\tau)] \\ &= \frac{I_{\mathrm{in}}(\omega)G(I_0)\exp(i\omega t)}{1 - G(I_0)\exp(-i\omega\tau)}, \end{aligned} \tag{8}$$

where $G(I_0) = \sqrt{G_{\mathrm{open}}}$ is a parameter related to the number of cycles $n$, and the value is equal to the open loop current gain of OEO under the condition of small signal approximation. $\tau$ is the time delay of the OEO loop. The power of output RF signal is written as

$$P_{\mathrm{out}}(\omega) = |I_{\mathrm{out}}(\omega,t)|^2 RH(\omega) = \frac{I_{\mathrm{in}}(\omega)^2 G(I_0)^2 RH(\omega)}{1\text{–}2\,G(I_0) + G(I_0)^2}, \tag{9}$$

where $R$ is resistance, $H(\omega)$ is the relative frequency response of the DFB laser[14] and set as $H(2\pi f_m) = 1$. The gain of the detection system for the RF signal can be expressed as

$$G_{\mathrm{sys}} = \frac{H(\omega)G_{\mathrm{open}}}{1 + G_{\mathrm{open}} - 2\sqrt{G_{\mathrm{open}}}}. \tag{10}$$

When the RF signal is located at the relaxation oscillation frequency, it will obtain the max $G_{\mathrm{sys}}$. So, the tunability of the detection system can be realized by tuning $f_m$, which changes with the bias current of the laser. A simulation for the maximum $G_{\mathrm{sys}}$ with $G_{\mathrm{open}}$ is carried out based on Eq. (10) in Fig. 3. With $G_{\mathrm{open}}$ increasing, the gain for signal at $f_m$ increases.

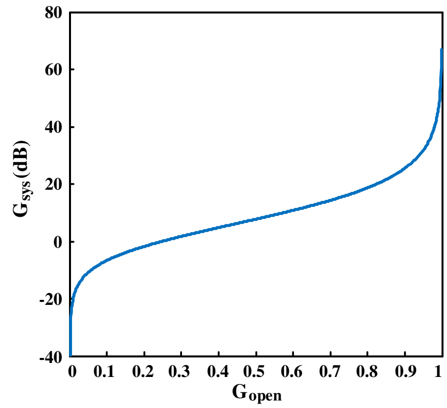


**Fig. 3.** Simulation for the max $G_{\mathrm{sys}}$ with $G_{\mathrm{open}}$.

### 2.2. Noise performance and detection sensitivity

The detection sensitivity is defined as the minimum detectable input RF power, which is determined by the oscillation modes of the OEO. The power of the oscillation modes is determined by the noise power and gain. In the conventional OEO loop, the total noise is composed of shot noise, thermal noise, and the laser's relative intensity noise (RIN). In this system, the EDFA will introduce amplifier spontaneous emission (ASE) noise. So, the beat noise between the signal and ASE (S-ASE) as well as the beat noise between ASE and ASE (ASE-ASE) should be taken into account.

The power of the thermal noise can be expressed as

$$P_{\mathrm{th}} = 4K_B T B_e, \tag{11}$$

where $K_B$ is the Boltzmann constant, $T$ is the ambient temperature in Kelvin of 300 K, and $B_e$ is the bandwidth of the electric receiver of 1 kHz. The shot noise is proportional to the detected photocurrent $I_d$, which can be written as

$$P_{\mathrm{shot}} = 2qI_d R_L B_e, \tag{12}$$

where $q$ is the electron charge, and $R_L$ is the load resistance of 50 Ω. The noise power of the laser's RIN is expressed as

$$P_{\mathrm{RIN}} = \frac{I_d^2}{2}10^{\frac{\mathrm{RIN}}{10}} R_L B_e, \tag{13}$$

where the RIN of the laser in the experiment is −160 dB/Hz. The output of the EDFA includes the amplified optical signal and the ASE noise. So, the beat noise between S-ASE and the beat noise between ASE-ASE are induced on the PD, which can be expressed as

$$\begin{aligned} P_{\text{S-ASE}} &= 4(r_{\mathrm{PD}}G_{\mathrm{EDFA}}P_{s,\mathrm{in}})r_{\mathrm{PD}}S_{\mathrm{ASE}}B_e R_L \\ &= 4(I_d - r_{\mathrm{PD}}S_{\mathrm{ASE}}B_o)r_{\mathrm{PD}}S_{\mathrm{ASE}}B_e R_L, \end{aligned} \tag{14}$$

$$P_{\text{ASE}-\text{ASE}} = \frac{1}{B_o} R_L \int_{-B_e}^{B_e} I_{\text{ASE}}^2 \left(1 - \frac{|f|}{B_o}\right) \mathrm{d}f = r_{\text{PD}}^2 S_{\text{ASE}}^2 (2B_o - B_e) B_e R_L, \quad (15)$$

where $P_{s,\text{in}}$ is the input optical signal power before the EDFA, $B_o$ is the optical bandwidth of the ASE with 40 nm at 1550 nm, $S_{\text{ASE}}$ is the power spectral density of the ASE noise with −134.7 dBm/Hz, and $I_{\text{ASE}}$ is the photogenerated current of the ASE noise. According to Eqs. (11)–(15), the total system noise can be expressed as

$$\begin{aligned} P_{\text{noise}} &= P_{S\text{-ASE}} + P_{\text{ASE-ASE}} + P_{\text{th}} + P_{\text{shot}} + P_{\text{RIN}} \\ &= 4(I_d - r_{\text{PD}} S_{\text{ASE}} B_o) r_{\text{PD}} S_{\text{ASE}} B_e R_L + r_{\text{PD}}^2 S_{\text{ASE}}^2 (2B_o - B_e) B_e R_L \\ &\quad + 4K_B T B_e + 2qI_d R_L B_e + \frac{I_d^2}{2} 10^{\frac{\text{RIN}}{10}} R_L B_e. \end{aligned} \quad (16)$$

A simulation for the noise power of the open loop system with different output current $I_d$ based on Eqs. (11)–(16) is carried out and plotted in Fig. 4. In the simulation, the gain of the EDFA is fixed, and $I_d$ changes with the power of the optical signal. When $I_d$ is less than 0.1 mA, the beat noise between ASE-ASE is the main noise. With $I_d$ increasing, the beat noise between S-ASE increases and becomes the main noise. The ASE noise of the EDFA plays a major role in the total noise. The use of a narrow-band optical filter to filter out the optical signal can effectively reduce the total noise of the detection system.

According to the loop oscillation theory[14], the power of the oscillation mode can be expressed as

$$P_{\text{mode}} = \frac{P_{\text{noise}} H(\omega)}{1 + G_{\text{open}} - 2\sqrt{G_{\text{open}}}}. \quad (17)$$

Set $P_{s,\text{in}}$ at 4 dBm and $f_m$ at 3 GHz, a simulation of the mode power at different frequencies is carried out according to Eqs. (6), (16), and (17). The results are plotted in Fig. 5. For the determined $G_{\text{open}}$, the power of the oscillation mode is not equal, which changes with $H(\omega)$. It reaches the maximum at the relaxation oscillation frequency. At the same time, with the open loop gain increasing, the power will increase correspondingly. The detection sensitivity is the minimum detectable power of the RF signal, which can be expressed as

$$P_{\min} = \frac{P_{\text{mode}}}{G_{\text{sys}}} = \frac{P_{\text{noise}}}{G_{\text{open}}}. \quad (18)$$

From Eqs. (10) and (18), it can be seen that, with the open loop gain increasing, the system gain for the RF signal will increase, and the detection sensitivity will be improved.

## 3. Results and Discussion

### 3.1. Gain property based on OEO

The RF detection system is set up based on the structure shown in Fig. 1. Once the bias current of the laser is fixed, only the signal aligned with the oscillation frequency can get the maximum gain. We set the bias current at 10 mA (threshold current is 8 mA) and adjust the open loop gain to make the system work at the multi-mode oscillation state, as shown in Fig. 6. In Fig. 6(a), the span is 2 GHz. The inset is the spectrum when no RF signal is injected into the system. The power of the oscillation modes is not equal, and the trend is basically the same as the modulation response of the DFB laser at a certain bias current, as shown in Fig. 5. The experimental results are consistent with the simulation results. Set the power of input RF signals ($f_1 = 2.618255$ GHz and $f_2 = 2.61834$ GHz) at −75 dBm. The RF signal $f_1$ is detected, while $f_2$ cannot be distinguished from the oscillation modes. When the span is set at 500 kHz in Fig. 6(b), the power of $f_1$, which matches the oscillation mode, is −59.3 dBm, and it is amplified by 15.7 dB. However, the power of $f_2$, which mismatches with the oscillation mode, is −80 dBm, and it gets the largest loss of 5 dB. The spacing of the oscillation modes is 180 kHz, which is determined by the loop length, including the 1.1 km SMF, the pigtails of the optoelectronic devices, and the erbium-doped fiber in the EDFA. The noise floor of the system is the peak power of the oscillation modes, which is −80.5 dBm. If the power of the output RF signal is below the

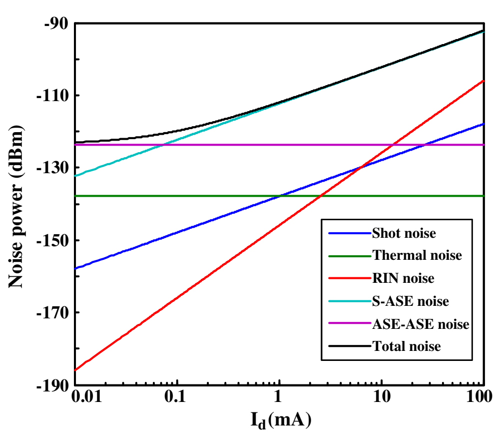


**Fig. 4.** Noise power with different photocurrents.

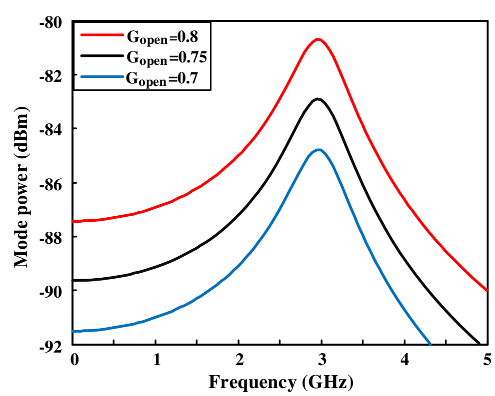


**Fig. 5.** Sidemode power at different frequencies.

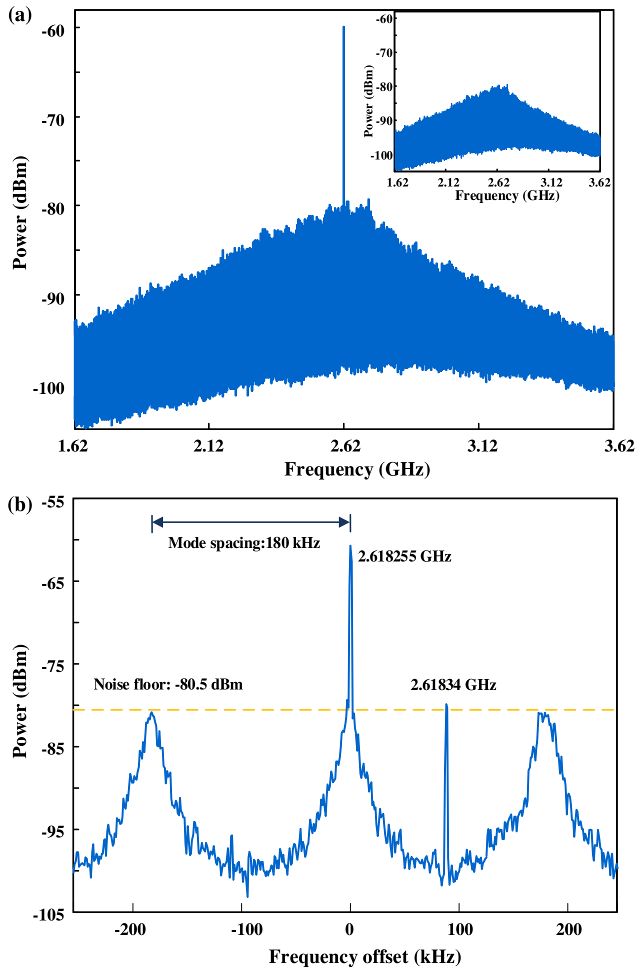


Fig. 6. Electrical spectra of the output RF signal: (a) span is 2 GHz, (b) span is 500 kHz.

noise floor, it cannot be distinguished from the oscillation modes.

For the RF signal at different frequencies, the amplification property is also investigated. At first, the delay time of the OTDL is set at 0 ps. According to the principle, the RF signal, which matches the oscillation mode located at the relaxation oscillation frequency, will get the largest gain. By adjusting the bias current of the laser, the relaxation oscillation frequency will change accordingly. Thus, amplifying the RF signal at different frequencies is realized. When the bias current changes from 8 mA to 12 mA, the RF signal acquires amplification within 1–4.5 GHz, as shown in Fig. 7. During the detection range, the power of the output RF signal is above −75 dBm, which exceeds the power of the RF source. The max gain reaches 17.88 dB at 2 GHz, which is 7.38 dB more than the system in Ref. [14]. However, the gain rolls down to 3.9 dB as the RF signal frequency increases to 4.5 GHz because the 3 dB bandwidth of the transmission response of the laser increases. The detection frequency is limited by the low-frequency response caused by the inherent characteristics of the DFB laser, which has been researched in our previous work[10].

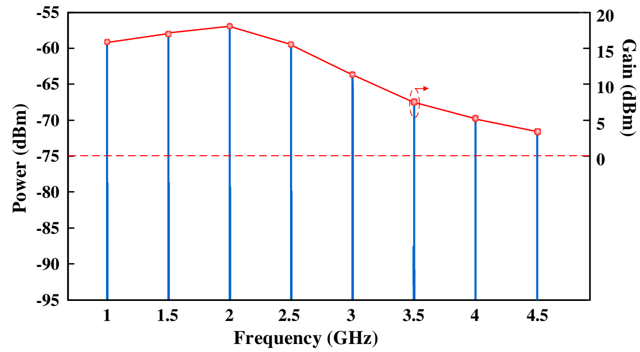


Fig. 7. RF signals at different frequencies are amplified.

## 3.2. No blind zone during the detection range

When the loop length is fixed, the interval between the oscillation modes is determined, and the system cannot provide gain for the RF signals, which mismatches with the oscillation modes. The problem can be solved by adjusting the delay time of the OTDL, which changes the loop length slightly. At first, the RF signal at 2.61825 GHz with −75 dBm is injected into the system. By increasing the delay time by the step of 50 ps, the mode spacing will decrease, and the oscillation modes will all shift to the direction of low frequency, as shown in Fig. 8(a). Figure 8(b) is the power of the detected RF signal. Within the 350 ps delay time, the RF power decreases at first and then increases to 60.8 dBm because the matched oscillation mode moves gradually away from the RF signal, while the next mode is closer to the RF signal and provides gain for it. That is to say, within 350 ps delay time, the next oscillation mode will be closer to the front one and coincide with it. Then, the RF signal at the frequency from 2.61825 GHz to 2.61843 GHz with the step of 30 kHz is injected to the system. By tuning the delay time to move the oscillation mode until it aligns with the RF signal at different

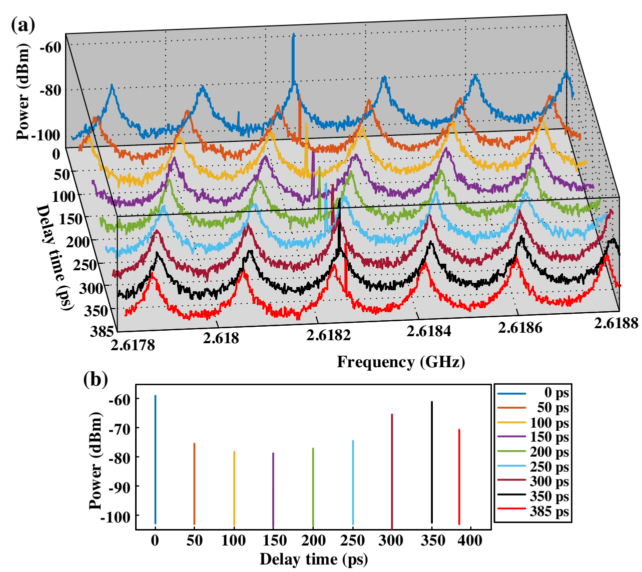


Fig. 8. Electrical spectra at 2.61825 GHz when the delay time is different.

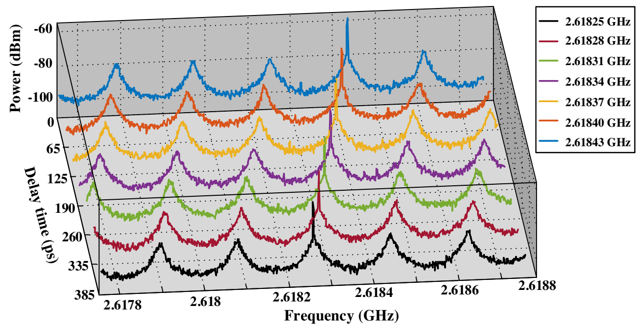


**Fig. 9.** Electrical spectra of the detected RF signal at different frequencies with corresponding delay time when acquiring the max gain.

frequencies, all RF signals can get amplified like the results shown in Fig. 9. According to Eq. (7), for the 4.5 GHz RF signal, the required delay time is just 220 ps. However, it increases to 1000 ps for the 1 GHz RF signal. All in all, by adjusting the bias current of the DFB laser and the delay time, no matter what frequency the RF signal is within 1–4.5 GHz, the system will detect it and provide gain for it.

### 3.3. Sensitivity, gain dynamic range, and stability

The sensitivity is defined as the detectable input RF power, which is an important parameter for the system. The RF signal with the frequency of 2.618255 GHz is injected to the system. The input RF power is decreased from −75 dBm until it cannot be distinguished from the oscillation modes. The electrical spectra are shown in Fig. 10. The noise floor is −80.5 dBm. When the input RF power is decreased to −95 dBm, it is a bit higher than the noise floor. So, the sensitivity is −95 dBm, which is 8 dB higher compared with that in Ref. [14].

On the other hand, the gain dynamic range property is also investigated, which is defined as the difference between the sensitivity and the highest input power when it equals the output power. Increasing the input power from −95 dBm to −10 dBm, the detected RF power is measured and plotted in the inset of Fig. 10. When the input power is lower than −35 dBm, the gain of the system is constant (15 dB), while the gain decreases to zero when the input power rises to −10.5 dBm. Accordingly, for the RF at 2.618255 GHz, the gain dynamic range is 84.5 dB.

Next, we research the stability of the system for the RF signal with different power. The frequency of the RF signal is set at 4.499963 GHz. In Fig. 11(a), using the "max hold" function of the ESA to mark the maximum power and "min hold" function to mark the minimum power of the signal, they are represented by solid lines and dotted lines, respectively. With the RF power increasing from −95 dBm to −75 dBm, the fluctuation of the detected signal power decreases from 2.9 dB to 0.63 dB, as shown in the inset of Fig. 11(a). The power fluctuation of the signal will be consistent with the oscillation mode fluctuating gradually as the signal power decreases. Then, fixing the power at −75 dBm, the stability at different frequencies is measured and plotted in Fig. 11(b). The results show that the detection system has the same stability performance for different frequency signals.

Finally, the detection performance for the modulated RF signal is investigated. The 2.618255 GHz RF signal with 2.4, 4.8, 10, and 20 ksps quadrature phase-shift keying (QPSK) data is applied to the system. The RF power is fixed at −75 dBm. The detected signal is measured by the vector signal analyser (VSA) module in the ESA, and the corresponding results are plotted in Fig. 12. As we can see, the constellation of the signal is clear. The error vector magnitudes (EVMs) are 5.59%, 7.97%, 11.49%, and 21.28%, and the corresponding signal-to-noise ratios (SNRs) are

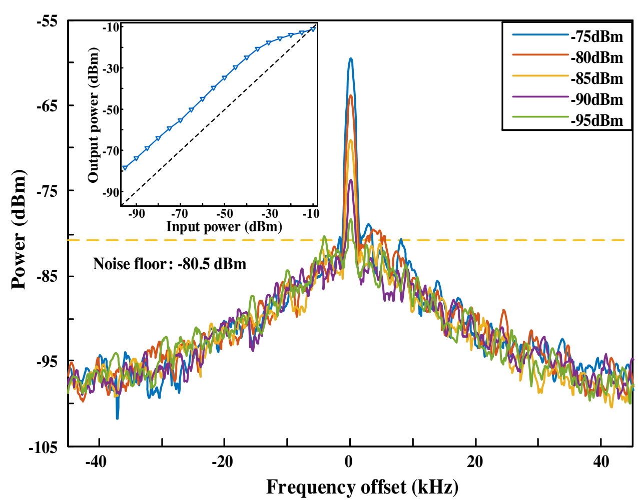


**Fig. 10.** Electrical spectra of the detected signals at 2.618255 GHz with different input power.

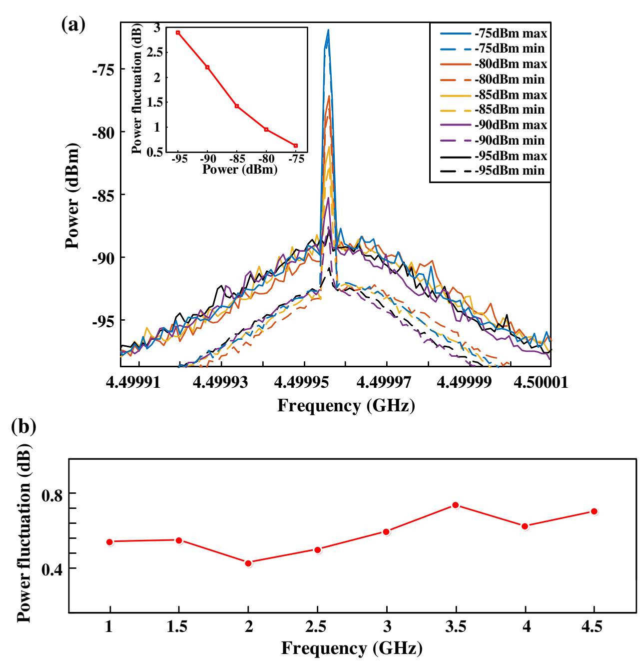


**Fig. 11.** Stability of the detected signal. (a) 4.499963 GHz signal with different power. (b) Power fluctuation of the signal with −75 dBm at different frequencies.

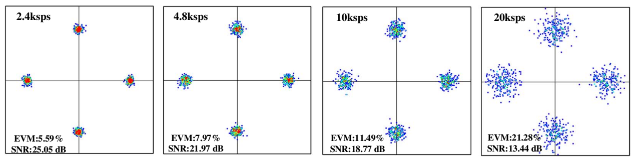


**Fig. 12.** QPSK constellation with different modulation rates at the power of −75 dBm with the center frequency of 2.618255 GHz.

25.05, 21.97, 18.77, and 13.44 dB, respectively. The bandwidth is limited by the 3 dB bandwidth of the oscillation mode (35 kHz in this system), which is generally used for the synchronized voice and asynchronous data signal transmission in the low-speed wireless communications, such as satellite phones, digital radio station, and other potential communications[8].

## 4. Conclusion

To conclude, in this paper, a simple method to realize weak RF signal detection with high sensitivity and no blind zone within the detection range is proposed and experimentally demonstrated. The system is based on the multi-mode OEO, which is realized by directly modulating the DFB semiconductor laser at the relaxation oscillation. The highly sensitive optical modulator and narrow band optical filter are avoided to make the system with low cost. The gain provided by the EDFA not only compensates the loss in the loop, but also makes the system work at the multi-mode oscillation state. The characteristics of the directly modulated detection system are analyzed for the first time, to the best of our knowledge. The experimental results are consistent with the simulation results. The RF signal aligning with the original oscillation modes can be amplified. By simply tuning the bias current of the laser, the system can detect RF signals from 1 to 4.5 GHz. Furthermore, by adjusting the delay time of the OTDL, the oscillation modes can move to search for and match with the unknown RF signal that mismatches with the original modes. So, there is no blind zone within 1–4.5 GHz. It provides the maximum gain of 17.88 dB for RF signals, and the sensitivity is as high as −95 dBm. The dynamic range is 84.5 dB at 2.618255 GHz. The power fluctuation of the output RF signal is below 0.8 dB, which shows that the power stability of the system is great. The system has potential for weak RF signal detection, especially for high accuracy and full coverage measurement.

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