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基于 DFB 腔注入锁定效应的可调谐光电振荡器

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摘　要:提出一种基于分布反馈光注入锁定效应的可调谐光电振荡器,其环路主要由马赫曾德尔调制器、光电探测器、环形器、分布反馈激光器和射频放大器顺接而成.分布反馈激光器是系统关键器件,通过分布反馈激光器光注入锁定效应,分布反馈腔在光域实现了微波光子滤波器功能,无需传统光电振荡器必须的射频带通滤波器.同时,由于分布反馈激光器注入锁定提高了环路 Q 值,因此系统可采用短环路结构,从而降低了光纤因温度敏感对微波信号稳定性的影响并减小了整个系统的尺寸.另外,通过调节注入光波长和功率可改变该微波光子滤波器的中心频率,从而可实现系统的可调谐性.理论分析了该光电振荡器的原理和微波光子滤波器的调谐性,在此基础上开展了实验验证.结果表明该光电振荡器能够产生 18.7 ~21.6 GHz 的可调微波信号,在 1 kHz 频偏处的相位噪声为－90 dBc/Hz.

关键词:光电子学;光电子器件;注入锁定;微波振荡器;分布反馈激光器
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Tunable Optoelectronic Oscillator Based on Injection-locking Effect in Distributed Feed-back Laser Diode

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Abstract: A tunable optoelectronic oscillator was proposed by utilizing optical injection-locking effect in a distributed feed-back laser diode. The optoelectronic oscillator loop mainly consists of an intensity modulator, a photodetector, an optical circulator, a distributed feed-back laser diode and a broad band radio frequency amplifier. In the proposed configuration, the distributed feed-back laser diode is key device. By utilizing injection locking of distributed feed-back laser diode rather than the commonly used radio-frequency band-pass filter, a high Q microwave filter is formed in optical domain, and short optoelectronic oscillator loop could be used in the proposed scheme. Thereby the effect of temperature sensitive of fiber on microwave signal stability can be declined and the system size can be reduced. Meanwhile, the central frequency of the microwave filter could be simply tuned and the tunability could be realized by tuning the wavelength and the injection power of the injection light. Theoretical analysis of the optoelectronic oscillator as well as the tunability of microwave filter was provided. Thus, experiment was done to verify the theoretical analysis. The results show that the proposed optoelectronic oscillator can produce the microwave signal with tunable range from 18. 7 GHz to 21. 6 GHz, and the measured phase noise at 1 kHz offset is －90 dBc/Hz.

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0 Introduction

Microwave signal source with low phase noise，high spectral purity and stability is important in many applications such as radar，communications，sensor networks and Radio-Over-Fiber（ROF） systems[1-3]. During the past two decades，numerous photonic techniques have been proposed to generate microwave signals[4-8]. Among these techniques，microwave generation using an Optoelectronic Oscillator（OEO）has been considered as a significant solution[9-11]. For an OEO system，the optical fiber in an OEO loop is used as an energy-storage component，and long fibers benefit the Q value of the OEO loop. However，long fiber lengths may cause small cavity mode spacing，which creates difficulty for oscillation mode selection. In principle，the oscillation frequency is the most common part of the cavity modes and the center frequency of the electric band pass filter. This means an Electric Band Pass Filter（EBPF）is necessary for selecting one of the modes to give the oscillation frequency. Unfortunately，single mode oscillation is hard to achieve in practice，even for short loop lengths[9].

Considering the flexibility of an OEO，frequency tunability is an important characteristic. According to the operation principle of an OEO，a tunable filter is desperately required to implement the tunability，such as a tunable electric filter or microwave photonic filter[12-13]. Although most of these schemes are feasible，they make the OEO system more complex or expensive to produce.

Recently，Jiang et al. have reported an injection-locked OEO with single-mode operation as well as precise oscillation frequency[14]. By utilizing the injection-locking effect in a Fabry-Pérot Laser Diode（FP-LD），a strong 20th sideband was generated from a 1 GHz modulated optical carrier and injection locking of the OEO oscillation frequency. In that case，the behavior of a FP-LD was regarded as a high Q optical filter，which was able to select and amplify one mode from a group of modes with minimal mode spacing. Therefore，it has potential to implement a filtering function in an OEO system.

In this paper，we proposed and demonstrated a tunable OEO by utilizing optical injection-locking effect in a Distributed Feed-Back（DFB）laser diode. Different from other schemes in Refs. [9，12-14]，this OEO provided a compact and cost-effective OEO configuration without using an electric band pass filter. By utilizing injection locking of DFB laser diode rather than the commonly used radio-frequency EBPF，a high Q microwave filter is formed in optical domain. Meanwhile，the central frequency of the high Q microwave filter could be simply tuned by tuning the wavelength and the injection power of the injection light. Theoretical analysis of the optoelectronic oscillator as well as the tunablity of microwave filter was provided. Thus，experiment was done to verify the theoretical analysis.

1 Operation principle

1.1 Possible oscillation modes

Fig. 1 gives the principle of the proposed OEO system. In this system，an External Cavity Laser（ECL）outputs a Continuous Wave（CW）with wavelength of λ_0，and the wavelength is tunable. The optical wave was amplified by an Erbium-Doped Fiber Amplifier（EDFA），and its polarization state was controlled by a Polarization Controller（PC）. The output of the PC was launched into an OEO loop，which mainly consists of an intensity modulator，a photodetector，an optical circulator，a DFB laser diode and a broad band RF amplifier.

We firstly derive the amplitude of the oscillating signal. As well known，the output of an OEO can be written as [15]

$$\widetilde{V}_{\text{out}}(\omega,t)=\widetilde{F}(\omega)G(V_0)\ \widetilde{V}_{\text{in}}(\omega,t) \tag{1}$$

where $\widetilde{V}_{\text{out}}(\omega,t)$ and $\widetilde{V}_{\text{in}}(\omega,t)$ are complex input and output voltages，$\widetilde{F}(\omega)$ and $G(V_0)$ are the loop frequency response and the voltage gain，respectively. Like other oscillators[16-17]，the oscillation of the proposed OEO starts from noise transient，which is then built up and sustained with feedback at the level of the oscillator output signal. The noise transient can be viewed as a collection of sine waves with random phases and amplitudes. To simplify our derivation, we use this noise input with the linearized expression of Eq. (1) for the loop response. Single-frequency component of the noise spectra can be written as

$$\widetilde{V}_{\mathrm{in}}(\omega,t)=\widetilde{V}_{\mathrm{in}}(\omega)\mathrm{e}^{\mathrm{j}\omega t} \tag{2}$$

where $\widetilde{V}_{\mathrm{in}}(\omega)$) is a complex amplitude of the frequency component.

Once the noise component of Eq. (2) is in the oscillator, it would circulate in the loop, and the recurrence relation of the fields from Eq. (1) is

$$\widetilde{V}_n(\omega,t)=\widetilde{F}(\omega)G(V_0)\ \widetilde{V}_{n-1}(\omega,t-\tau) \tag{3}$$

where τ is the time delay resulting from the physical length of the feedback and n is the number of times the field has circulated around the loop.

The total field at any instant of time is the summation of all circulating fields. Therefore, the signal measured at the RF input to the modulator for the case when the open-loop gain is less than unity can be expressed as

$$\widetilde{V}(\omega,t)=G_{\mathrm{A}}\widetilde{V}_{\mathrm{in}}(\omega)\sum_{n=0}^{\infty}\widetilde{F}(\omega)G(V_0)\mathrm{e}^{\mathrm{j}\omega(t-n\tau)}=\frac{G_{\mathrm{A}}\widetilde{V}_{\mathrm{in}}(\omega)\mathrm{e}^{\mathrm{j}\omega t}}{1-\widetilde{F}(\omega)G(V_0)\mathrm{e}^{\mathrm{j}\omega\tau}} \tag{4}$$

where G_A is the amplifier′s voltage gain. Therefore, the corresponding power of the circulating noise at frequency ω is

$$P(\omega)=\frac{|\widetilde{V}(\omega,t)|^2}{2R}=\frac{G_{\mathrm{A}}|\widetilde{V}_{\mathrm{in}}(\omega)|^2\mathrm{e}^{\mathrm{j}\omega t}}{1+|\widetilde{F}(\omega)G(V_0)|^2-2|\widetilde{F}(\omega)||G(V_0)|\cos[\omega\tau+\varphi(\omega)+\varphi_0]} \tag{5}$$

where $\varphi_0=0$ if $G(V_0)>0$ and $\varphi_0=\tau$ if $G(V_0)<0$.

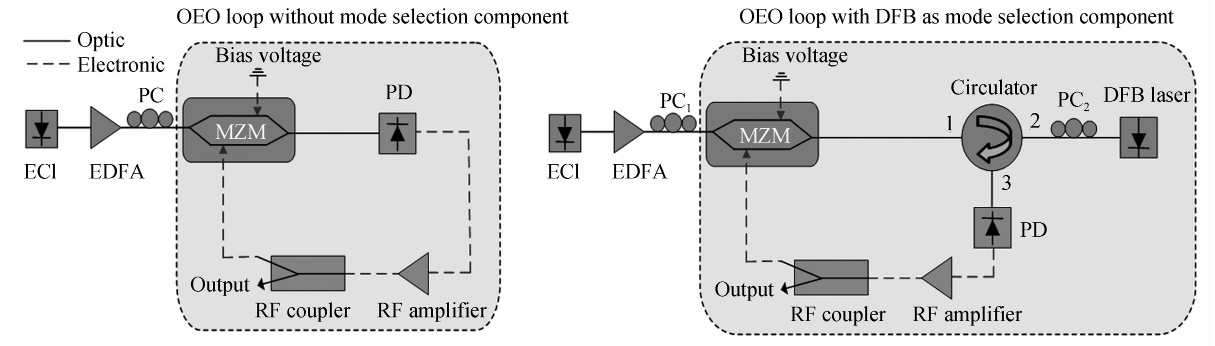
Therefore, for a constant $\widetilde{V}_{\mathrm{in}}(\omega)$, the frequency response of an OEO loop without mode selection component as shown in Fig. 1(a) has equally spaced peaks similar to those of a Fabry - Perot resonator, Fig. 1 (c) shows the corresponding frequency response. These peaks are located at the frequencies determined by

$$\omega_k\tau+\varphi(\omega_k)+\varphi_0=2k\pi, k=0,1,2,3,\cdots \tag{6}$$

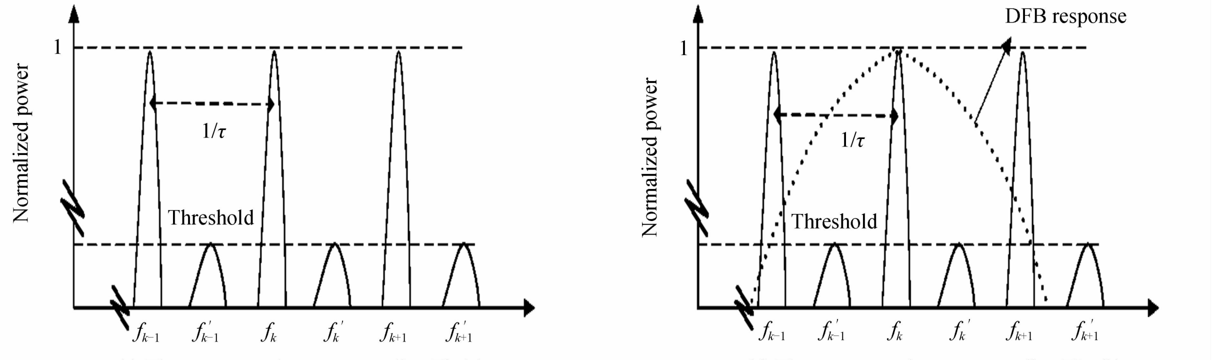
where k is the mode number. In Fig. 1(c), each peak corresponds to a frequency component resulting from the coherent summation of all circulating fields in the loop at that frequency. In the Fig. 1 (c) and (d), $f_{k-1}\ f_k\ f_{k+1}$ represent one of the sets of the modes above the threshold; $f'_{k-1} f'_k, f'_{k+1}$ represent one of the sets of the modes below the threshold. As the open-loop gain increases, the magnitude of each peak becomes larger and its shape becomes sharper. These peaks are the possible oscillation modes of the OEO. When the open-loop gain is larger than unity, each time a noise component at a peak frequency travels around the loop, it is amplified and its amplitude increases geometrically-an oscillation is started from noise.

1.2 Modes selection and tunability

From the discussion above, it is clear that a group of periodically possible oscillation modes can be generated by using the OEO loop of Fig. 1 (a). Although these periodical modes have large closed-loop gain at beginning, with these modes′ power increasing and reaching the nonlinear threshold, the power will be transferred to other modes as nonlinear effect such as four waves mixing when these modes are modulated by Mach-Zehnder Modulator (MZM) and fed back into the OEO loop. Meanwhile, there are intense intramodal competitions among the same group modes[15]. Therefore, stable single-mode oscillation cannot be generated based on the OEO loop of Fig. 1 (a). To get single-mode oscillation, an RF high Q EBPF is needed in conventional schemes[9,12]. Comparing with those schemes, the DFB laser is a most important device in our proposed scheme as shown in Fig. 1 (b). Because the DFB has a single-mode output, the DFB cavity has very narrow gain region. Therefore, when a group of periodically possible oscillation modes are sent into the DFB cavity, one of the modes will be locked and amplified in optical domain if it locates at gain region of DFB cavity, and the other modes are suppressed as shown in Fig. 1 (d). We should note that large side mode spacing ($1/\tau$) is needed to prevent other modes of the same group be amplified by DFB cavity. Because the injection locking threshold is very small, the injection locking of the DFB laser would form a high Q microwave filter to perform microwave frequency selection. Due to the feedback modulation, the selected mode was sent into the DFB laser diode once more, the modulation sideband is enhanced. As a whole feedback system, it should be considered that an OEO is a multimode system with a group of side modes. If the first order modulation side band of the beat signal only fell into one of the oscillations modes and the phase of the beat signal matches the oscillation condition of the OEO system, the beat signal is able to be enhanced by the feedback process, and then a stable oscillation can be set up. Obviously, the output frequency can be tuned by changing λ_0, since the beat frequency is determined by $\Delta\lambda=|\lambda_0-\lambda_f|$, where λ_f is lasing wavelength of DFB laser. Meanwhile, as DFB laser has functions of high Q microwave filter in the OEO loop, long fiber is not needed to increase Q value of the OEO loop. Therefore, we could use a short OEO loop to get large side mode spacing.



(a) An OEO loop without DFB (b) An OEO loop with DFB



(c) The output modes corresponding Fig(a) (d) The output modes corresponding FIg.(b)

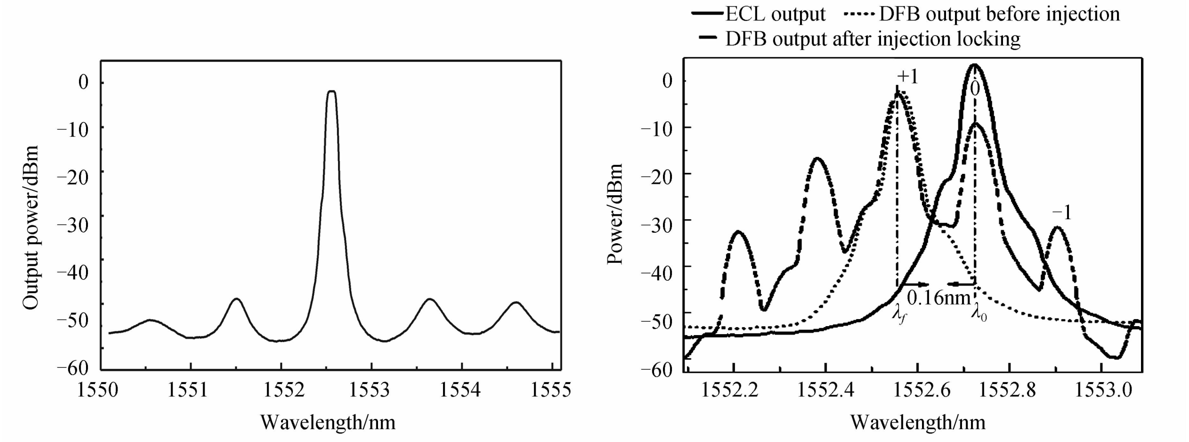
Fig. 1 Two types OEO loop and corresponding output modes

2 Experimental setup

Based upon the setup described in Fig. 1(b), experimental measurements were performed. A tunable ECL was used to generate a tunable optical carrier. The polarization state was controlled by PC_1 for the best modulation after its power was amplified by EDFA to 10 dBm. In the OEO loop, the PC_1 output first passed through a MZM with a 3 dB bandwidth of 40 GHz, and was then sent into $Port_1$ of an Optical Circulator (OC). The output light from $Port_2$ of the OC was injected to a DFB laser with a lasing wavelength (λ_f) of 1552.56 nm. Next, PC_2 was placed at $Port_2$ to select the injected Transverse-Electric (TE) mode as it could strongly affect the injection-locking efficiency and red-shift in DFB laser, and the injection power of the light was −2 dBm. After injection, the output signal of the DFB laser was launched into a PD with bandwidth of 30 GHz, which was employed to convert the optical signal into an electrical domain. After that the signal was amplified by an electric Amplifier (AE) centered at 20 GHz with a bandwidth of 4 GHz, it modulated optical carrier through the MZM again and feed back to the OEO loop. One of the RF coupler outputs was observed by an Electrical Spectrum Analyzer (ESA) with the spectrum range from 9 kHz to 26.5 GHz. As the discussion in operation principle section, the proposed scheme has a short OEO loop and it is 50 meters including pigtail of the components in the loop.

3 Experimental results and discussion

In our experiment, the DFB laser had a free-running lasing mode with a wavelength of 1 552.56 nm. The spectrum of the DFB free-running is shown in the Fig. 2(a), the side mode is suppressed and is 50 dB lower than the fundamental tone, the result shows that the DFB could output single longitudinal mode well. When the wavelength of the tunable ECL was set to equal 1 552.72 nm, it could cause approximately 0.16 nm wavelength differences between lasing mode and the injection light including the red-shift in the injection locking process. The corresponding optical spectra measured at Port$_3$ of the OC are shown in Fig. 2(b), and the red-shift can be observed by comparing the optical spectra before and after external light injecting. At first, the first side mode's power was not large enough, and competition and instability were obviously existed in the process to generate multi-orders. Once the +1 order mode's power exceeds the threshold, the +1 order side mode will be will be locked and amplified. After circulating in the cavity with multiple roundtrips, it will benefit the Q value from the cavity resonance, and the other modes are suppressed. From the Fig. 2(b), the power of the locked mode is higher 15 dB than other mode, which is high enough to strongly suppress the undesirable eigenmodes of the OEO through carriers competition in the injection locking process[18].

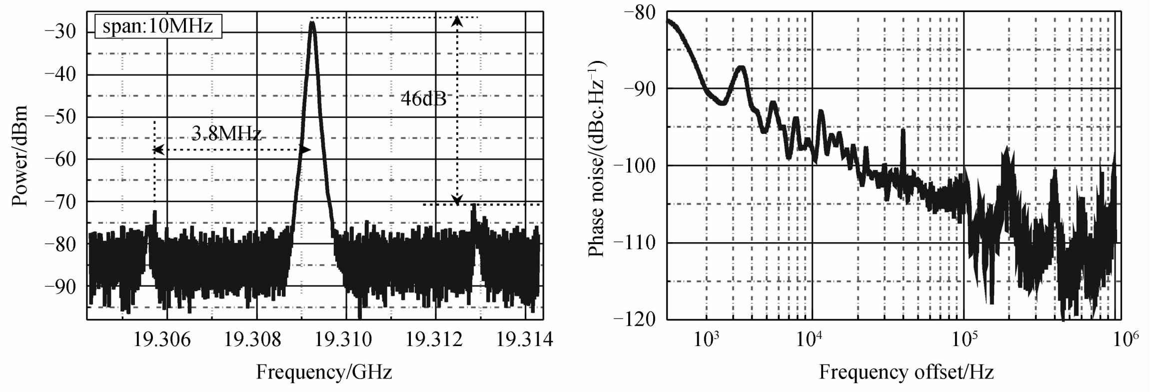


(a) Optical spectra of the output from ECL

(b) Optical spectra of the output from ECL, MZM and DFB

Fig. 2 Measured optical spectra of the output from ECL, MZM and DFB

The electronic microwave signal from the output port can be observed by the ESA. The corresponding RF spectrum is illustrated in Fig. 3(a). As shown in Fig. 3(a), a strong oscillation signal with a frequency of 19.3 GHz can be observed. The measured Side Mode Suppression Ratio (SMSR) was 46 dB and the side mode spacing was 3.8 MHz. The signal to noise ratio reached about 55 dB within the span of 5 MHz.



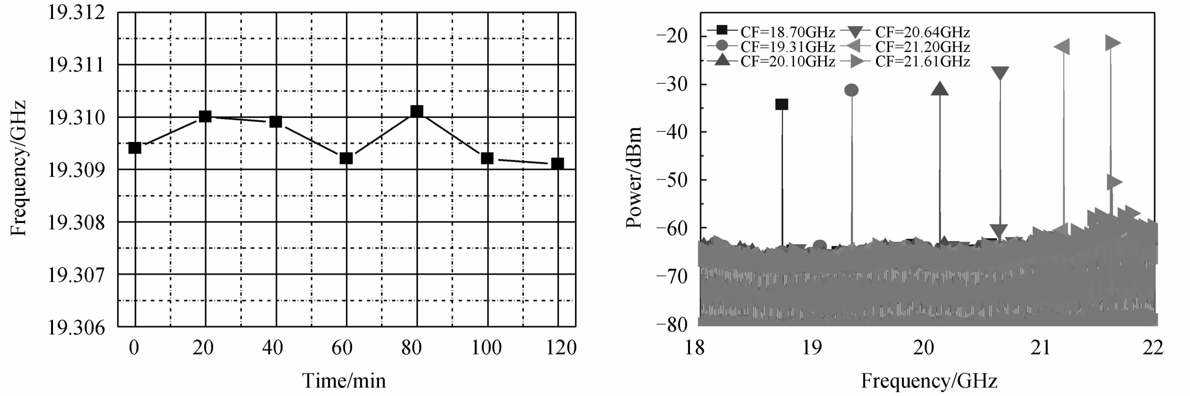
(a) Generated 19.3GHz microwave signal with span of the 10MHz

(b) Corresponding phase noise of Fig.(a)

Fig. 3 Measured RF spectra of the generated microwave signal and corresponding phase noise

The phase noise performance of the electronic microwave signal was also studied. Fig. 3(b) shows the single sideband phase noise spectra of the generated 19.3 GHz microwave signal. The phase noise of the 19.3 GHz at 1 kHz frequency offset can be read as −90 dBc/Hz, and it is −98 dBc/Hz at a 10 kHz offset frequency. The phase noise performance could be further improved by using multiple optoelectronic loops[19]. The results indicate that the generated signal was of good quality.

Because a short OEO loop was used in the proposed system, the instability affected by the fiber is reduced, and the frequency stability was mainly determined by tunable ECL, MZM and DFB. In our experiment, the MZM is a waveguide device, it has good stability, and we used a wavelength stabilized laser source, and high stable DC power supplies. At the same time, we controlled room temperature stays at near-constant by three air conditioners. Therefore, our system is high stable. To evaluate the stability of the system, the system was allowed to operate for a period of 20 min. Fig. 4(a) shows the frequency fluctuation of the generated microwave signal of 19.309 GHz is below 1 MHz within 120 min. In fact, if we use the temperature control boxes to accurately control the operation temperature of active device, the frequency stability can be improved. In addition, multi-loop (e. g. dual loop) can gain benefit in the frequency stability of the generated microwave[19].



(a) Frequency fluctuation of the generated microwave signal (b) Spectra with center frequency tuned from 18.7 to 21.6GHz

Fig. 4 Frequency stability and tunability of the proposed OEO

In order to demonstrate the tunability of our scheme, the output wavelength of ECL was changed gradually from 1 552.70 nm to 1 552.73 nm. As shown in Fig. 4(b), the corresponding RF signals were generated from 18.7 GHz to 21.6 GHz. It should be emphasized that theoretically, the tuning range of the system could be very broad, however, in our experiment it was limited by the bandwidth of AE.

4 Conclusion

We proposed and demonstrated a novel injection-locking based OEO to obtain tunable RF signals. Based on the injection-locking effect in DFB laser, one of the possible oscillation modes in the OEO system was able to be selectively amplified, and the frequency was decided by the difference between the optical carrier and the lasing mode of the DFB laser. This scheme could easily implement a tunable RF source without an electric filtering component. Meanwhile, the cost of whole system was reduced. In the experiment, the RF signal frequency was continually tuned from 18.7 GHz to 21.6 GHz and the phase noise at 1 kHz frequency offset was −90 dBc/Hz. The results shows that the proposed OEO provides a compact and cost-effective OEO configuration without using an electric band pass filter. It has good performance in flexibility and tunability.

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