A coupled optoelectronic oscillator with three resonant cavities*

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A new single-mode optoelectronic oscillator (OEO) with three coupled cavities is proposed and demonstrated. A Fabry-Perot (F-P) cavity fiber laser and an optical-electrical feedback branch are coupled together to construct an opto-electronic oscillator, where the F-P cavity fiber laser serves as a light source, and a modulator is placed in the laser cavity to implement reciprocating modulation, which simultaneously splits the laser cavity into two parts and forms a dual-loop configuration. To complete an optoelectronic oscillator, part of optical signal is output from the F-P cavity to implement the feedback modulation, which constructs the third cavity. Since only the oscillation signal satisfies the requirements of all the three cavities, a single-mode oscillation can be finally achieved. Three resonant cavities are successfully designed without adding more optoelectronic devices, and the side-modes can be well suppressed with low cost. The oscillation condition is theoretically analyzed. In the experimental demonstration, a 20 GHz single longitudinal mode microwave signal is successfully obtained.

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Optoelectronic oscillators (OEOs)[1-4] are widely concerned recently because they can generate high-quality microwave signals. For generating high-quality signals, a long optical fiber is usually used as the energy storage component in an oscillator loop, which can provide a very high cavity quality factor (Q)[2]. However, a long loop causes very small mode spacing, and the commercial radio-frequency (RF) filter is not able to select one of the modes and reject others[5].

In order to obtain single longitudinal mode signal, several solutions have been proposed. For instance, the first solution is an optoelectronic oscillator based on optical resonators with whispering-gallery mode[6-10], which has a high Q value and provides high side-mode suppression ratio, but its large insertion loss and poor tunability both limit the applications to some extent. The second solution is multiloop optoelectronic structure, which is the most popular method for side-mode suppression. Sun Bin et al[11] have proposed this configuration in 2012. Liang Jianhui et al[12] have proposed similar multiloop optoelectronic oscillator with optical loop and additional electrical loop. Although these two schemes show good performance, more optical or electric devices have to be used, which greatly increases the cost and makes the OEO system more complex. In order to reduce the cost of the system, Liang Gao et al[13] have proposed the configuration with optical dual loops. In this case, two loops are simply combined in optical domain with very low cost, but it can only form two loops due to the loop difference depends on two orthogonal polarization fields. Furthermore, E. Salik et al[14] have proposed a configuration of coupled optoelectronic oscillator (COEO), which is similar to a regenerative mode-locked laser, and the laser cavity and optoelectronic feedback branch naturally construct two loops. This scheme takes the advantage of the laser cavity to select oscillation mode and provide light source.

Compared with all the solutions, the multiloop configuration is a good choice for side-mode suppression. However, it should be emphasized that dual-loop structure can only make the mode spacing larger but can not exactly generate single longitudinal mode microwave signal. Although more loops can provide better side-mode suppression, it means that more optoelectronic components are required. How to simply design more loops with lower cost is significant work for OEO.

In this paper, we demonstrate a novel three-cavity COEO, which solves the defects of the conventional multiloop optoelectronic oscillators. The proposed COEO has no external light source and doesn't need more active components. Since the modes are selected by three cavities simultaneously, the single longitudinal

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mode microwave signal can be obtained.

The schematic diagram of the proposed three-cavity COEO is shown in Fig.1. The system can be regarded as two parts, which are Fabry-Perot (F-P) cavity fiber laser and photoelectric conversion branch. In the F-P cavity fiber laser, there is a Mach-Zehnder modulator (MZM) in the middle of the laser cavity, which modulates the optical field twice and splits the cavity into cavity 1 and cavity 2 with the lengths of L_1 and L_2, respectively. The photoelectric conversion branch constructs the cavity 3, which consists of a section of optical fiber with the length of L_3, a photodetector (PD), an RF filter and an electric amplifier. The branch can convert the optical signal into the electric signal, after which the electric signal feeds back to the RF port of the MZM to close the loop.

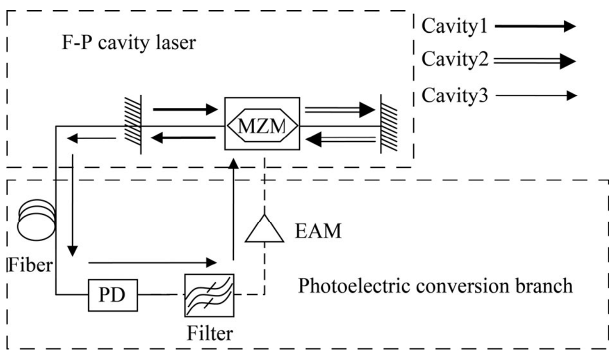


Fig.1 Configuration of the proposed three-cavity COEO

Obviously, compared with a conventional OEO, this COEO has three feedback loops with different lengths. Each oscillation mode with frequency of f_{osc} must add up in phase after each round trip:

$$f_{osc}=(l+1/2)/\tau_1=(m+1/2)/\tau_2=(n+1/2)/\tau_3 \quad ,$$

$$\text{or} \qquad f_{osc}=l/\tau_1=m/\tau_2=n/\tau_3 \quad , \tag{1}$$

where τ_i (i=1, 2, 3) are the delays of the loops determined by the lengths of cavities 1, 2 and 3, respectively, and l, m and n are all integers.

Similar to the oscillation requirement of a single loop OEO, the recursive relation can be expressed as

$$\tilde{V}_i(\omega)=[g_1\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_1)+g_2\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_2)+g_3\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_3)]\cdot\tilde{V}_{i-1}(\omega) \quad , \tag{2}$$

where $\tilde{V}_i(\omega)$ is the complex amplitude of the optical signal in the OEO after i cycles, and g_i (i=1, 2, 3) are the complex gains of the cavities 1, 2 and 3, respectively.

When the oscillation is stabilized, the total output is

$$\tilde{V}_{out}(\omega)=\sum_{i=0}^{\infty}[g_1\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_1)+g_2\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_2)+g_3\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_3)]\cdot\tilde{V}_i(\omega)=\frac{\tilde{V}_0}{1-\left[g_1\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_1)+g_2\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_2)+g_3\cdot\exp(\mathrm{i}\cdot\omega\cdot\tau_3)\right]} \,. \tag{3}$$

The corresponding RF power is

$$P(\omega)=\left|\tilde{V}_{out}(\omega)\right|^2/2R \quad , \tag{4}$$

where R is the resistance of the photoelectric detector. Substituting Eq.(3) into Eq.(4), we have

$$P(\omega)=\left|\tilde{V}_0\right|^2/\{2R[1+|g_1|^2+|g_2|^2+|g_3|^2+2|g_1|\cdot|g_2|\cdot\cos(\Phi_1-\Phi_2)+2|g_2|\cdot|g_3|\cdot\cos(\Phi_2-\Phi_3)+2|g_1|\cdot|g_3|\cdot\cos(\Phi_1-\Phi_3)-2(|g_1|\cdot\cos\Phi_1+|g_2|\cdot\cos\Phi_2+|g_3|\cdot\cos\Phi_3)]\} \,, \tag{5}$$

where

$$\Phi_i=\omega\cdot\tau_i+\varphi_i\,,\quad i=1,\ 2,\ 3 \quad , \tag{6}$$

where φ_i is the phase factor of the complex gain g_i.

As we know, the oscillation begins with the noise, so we must have

$$1+|g_1|^2+|g_2|^2+|g_3|^2+2|g_1|\cdot|g_2|\cdot\cos(\Phi_1-\Phi_2)+2|g_2|\cdot|g_3|\cdot\cos(\Phi_2-\Phi_3)+2|g_1|\cdot|g_3|\cdot\cos(\Phi_1-\Phi_3)-2(|g_1|\cdot\cos\Phi_1+|g_2|\cdot\cos\Phi_2+|g_3|\cdot\cos\Phi_3)=0 \,. \tag{7}$$

According to these equations, the oscillation can only be set up when oscillation frequencies in each loop satisfy Eq.(1), which means that one must have $|g_1|=|g_2|=|g_3|$, $\Phi_1=2\pi l$, $\Phi_2=2\pi m$ and $\Phi_3=2\pi n$. In other words, the optical signal should simultaneously satisfy the phase conditions determined by the three resonant cavities. Therefore, single-mode oscillation can be achieved.

In order to verify the theoretical analysis, an experiment is performed. Firstly, a dual-loop COEO with the experimental setup shown in Fig.2 is demonstrated as comparison.

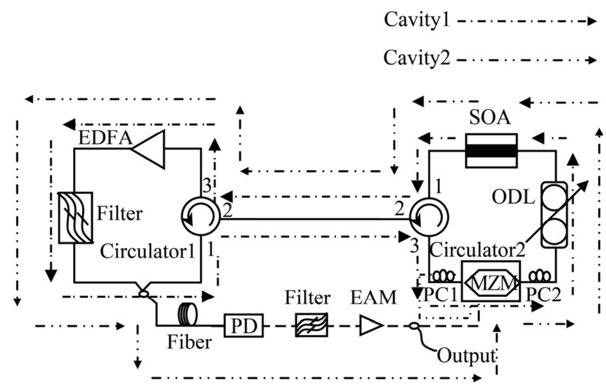
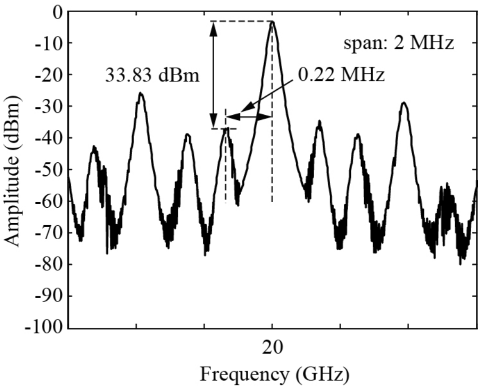


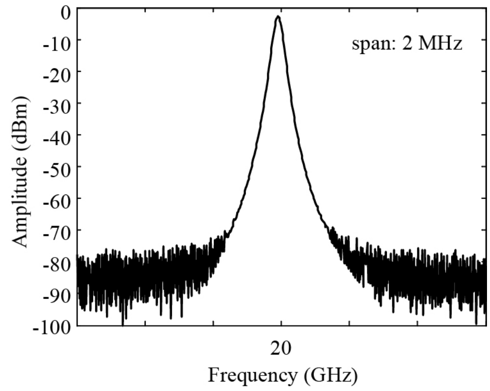
Fig.2 Experimental setup of the dual-loop COEO

As illustrated in Fig.2, the F-P cavity fiber laser includes an erbium-doped fiber amplifier (EDFA), a coupler, two circulators, an MZM, two polarization controllers (PCs), an optical fiber delay line (ODL) and a semiconductor optical amplifier (SOA), where these components are linked together by their pigtails. The circulators 1 and 2 form two reflection loops, which are equivalent to the reflecting mirrors of an F-P cavity. In the F-P cavity, a laser field can be set up due to the feedback between two reflection loops, whose wavelength is determined by the optical filter and set at 1 552.3 nm. In the right reflection loop, the optical field is modulated by MZM. The followed ODL is used to adjust the time delay of the signal, and the SOA is used to compensate the loss in the cavity. A part of optical signal from the left reflection loop is coupled out and passes through the optical fiber with length of 1 km, then launches into the PD with the optical power of –7.2 dBm. The used PD has the bandwidth of 30 GHz, and its output is filtered by an RF filter which is centered at 20 GHz with bandwidth of 30 MHz. The filtered electric signal finally feeds back to the MZM to close the OEO loop. Since the oscillation signal is modulated once by the MZM, the whole system is a dual-loop COEO structure. In the experiment, the pump current of the EDFA is about 200 mA, and the operating current of SOA is 300 mA.

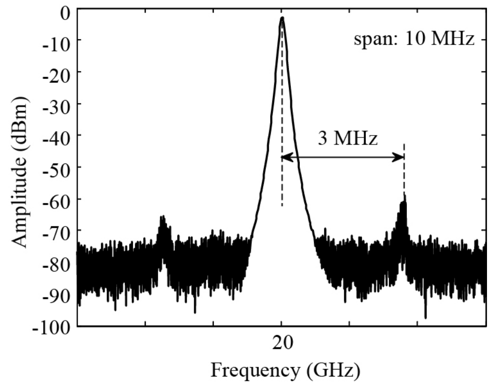
When this COEO system runs, the F-P cavity fiber laser and modulation index are sensitive to the polarization state. In order to achieve a stable oscillation with high side-mode suppression, the polarization state of the circulating field must be optimized by PC1 and PC2. If the polarization state is aligned inappropriately, many side-modes will appear, as shown in Fig.3(a). In Fig.3(a), it can be seen that the mode spacing is 0.22 MHz, which is decided by the 1 km-long cavity (the photoelectric conversion branch). However, when the polarization state is aligned appropriately, two loops select the oscillation mode at the same time, and the side-modes can be well suppressed. The corresponding RF spectrum is shown in Fig.3(b). It should be noted that the dual-loop structure can only enlarge the mode spacing. When we observe the spectrum with span of 10 MHz, the common modes of the two loops still exist, which is 3 MHz offset from the carrier as shown in Fig.3(c).



(a)



(b)



(c)

Fig.3 RF spectra of dual-loop COEO with (a) the polarization state aligned inappropriately and the polarization state aligned appropriately with frequency spans of (b) 2 MHz and (c) 10 MHz

Next, the position of the MZM is moved to the middle of the F-P laser cavity, as shown in Fig.4. In this configuration, the laser field transits from the left reflection loop into the MZM, and then returns through the right reflection loop. Therefore, the optical signal is modulated twice by the MZM in each round trip, and the whole system is a three-cavity COEO.

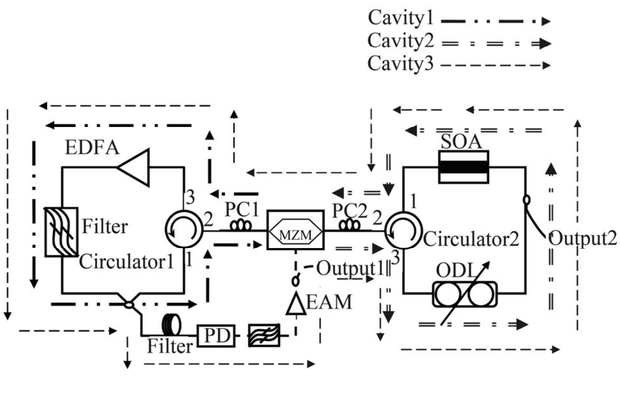


Fig.4 Experimental setup of the three-cavity COEO

Compared with the case of dual-loop COEO, Fig.5(a) is the spectrum of the three-cavity COEO, which presents good signal quality. Furthermore, when we observe the spectrum with span of 10 MHz shown in Fig.5(b), compared with the corresponding situation of the dual-loop COEO shown in Fig.3(c), the residual side-modes are vanished, which implies that a better mode selection or a higher side-mode suppression is implemented by the three-cavity configuration.

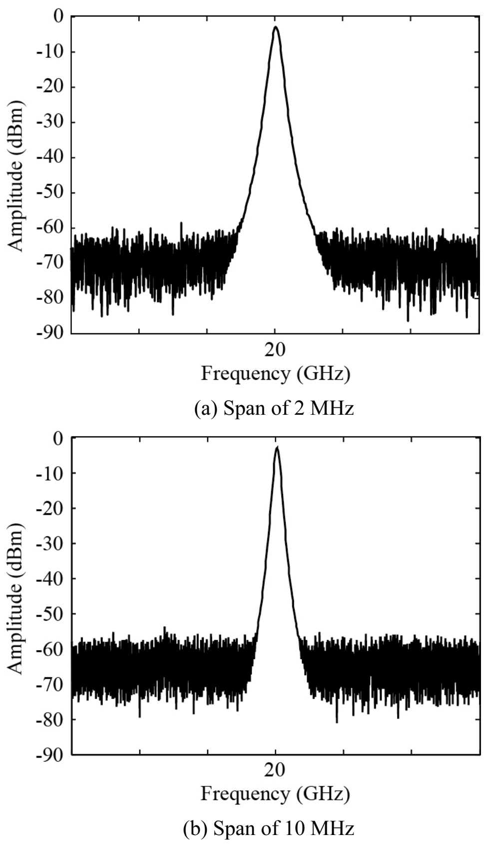


Fig.5 RF spectra of three-cavity COEO with frequency spans of 2 MHz and 10 MHz

Due to the limit of experimental condition, the phase noise measurement is not shown here. However, according to the RF spectrum, the proposed system still presents good performance, and the superiority of the three-cavity COEO can be observed. This design provides a simple way to realize three feedback loops without adding more optoelectronic devices. By comparing the experimental results of the dual-loop COEO and the three-cavity COEO, the side-modes of the three-cavity COEO are better suppressed and finally a single-mode oscillation is achieved by the three-cavity COEO.

In summary, we propose a three-cavity COEO with all-optical structure. Experimentally, the optoelectronic oscillator operating at frequency of 20 GHz is demonstrated, and the results agree with the theoretical prediction. With this scheme, the side-modes are well suppressed, and the single-mode output is obtained.

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