Polarization-maintained coupled optoelectronic oscillator incorporating an unpumped erbium-doped fiber

Tianhua Du (杜天华), Dan Zhu (朱 丹)*, and Shilong Pan (潘时龙)

The Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education,
Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
**Corresponding author: danzhu@nuaa.edu.cn*

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A polarization-maintained coupled optoelectronic oscillator (COEO) with its performance significantly improved by a short-length unpumped erbium-doped fiber (EDF) is reported and experimentally investigated. A 10 GHz optical pulse train with a supermode suppression ratio of 61.8 dB and a 10 GHz radio frequency signal with a sidemode suppression ratio of 94 dB and a phase noise of −121.9 dBc/Hz at 10 kHz offset are simultaneously generated. Thanks to saturable absorption of the 1 m unpumped EDF, which introduces relatively large cavity loss to the undesired modes and noise, the supermode suppression ratio and the phase noise are improved by 9.4 and 7.9 dB, respectively.

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Coupled optoelectronic oscillators (COEOs) have been widely studied in recent years due to their capability of simultaneously generating optical pulses and electrical signals with high quality[1–4], which is urgently required by microwave photonic radars, satellite payloads, and so on[5–7]. A generic COEO is combined by an optoelectronic oscillator (OEO) and a mode-locked fiber laser sharing an electro-optical modulator. The quality of the optical pulses generated from the mode-locked fiber laser loop and the radio frequency (RF) signal from the OEO loop is ensured by the positive feedback between the two loops. For optical pulse generation using a mode-locked fiber laser, one of the key performance indicators is the supermode suppression ratio. Since the mode-locked fiber laser loop is a multimode cavity, which supports multiple oscillating modes spaced by the cavity fundamental frequency, beating among these supermodes generates considerable or even dominating noise associated with the generated optical pulses. Several methods have been proposed to suppress the supermodes. One effective way is to incorporate narrowband filters, such as comb filters[8] and composite cavities[9], in the cavity, but the wavelength drift of the filters (or different cavities) would inevitably degrade the stability of the laser. Another method is to reduce the pulse amplitude fluctuations by introducing inhomogeneous loss (or intensity-dependent loss)[10] to the cavity. A typical inhomogeneous loss mechanism includes self-phase modulation followed by optical filtering[11], nonlinear polarization rotation effect[12], and optical pulse power feedback[13]. However, complex structures are needed and careful alignments are usually required.

Besides the supermode suppression ratio, the sidemode suppression ratio and phase noise of the generated RF signal are two other key performance indicators for COEOs[14]. In order to improve the sidemode suppression, we have proposed a stable COEO incorporating a length of unpumped erbium-doped fiber (EDF)[15,16]. However, the absorption of the undesirable sidemodes is relatively small, since the standing waves in the EDF to stimulate the spatial hole burning (SHB) effect are weak. To remedy this, a dual-loop structure with two different lengths of long fiber has to be applied to further suppress the sidemodes[15], or a specially designed structure has to be introduced to enhance the SHB effect[16].

In this work, we report a simple way to simultaneously generate optical short pulses with large supermode suppression and RF signals with large sidemode suppression and low phase noise by incorporating a short-length unpumped EDF into a polarization-maintained short-cavity COEO. Thanks to the relatively short length of the fiber laser cavity and optoelectronic cavity, both the optical and RF mode spacings are enlarged. Then, the unpumped EDF, serving as a saturable absorber, introduces a relatively large cavity loss to the undesirable low power modes and noise, which greatly improve the optical supermode suppression ratio and RF phase noise performance of the COEO. Weak saturable absorption is sufficient to guarantee significant improvement because the number of the optical and RF competing modes is reduced by the short cavity. An experiment is conducted. A high quality optical pulse train with a repetition rate of 10 GHz and an RF signal at 10 GHz are successfully generated. By incorporating a 1 m EDF with an absorption coefficient of 13 dB/m at 1530 nm, the supermode suppression ratio of the generated optical pulse is improved by 9.4 dB (to 61.8 dB), and the phase noise of the generated RF signal is improved by 7.9 dB (to −121.9 dBc/Hz at a 10 kHz offset), while the sidemode suppression ratio maintains 94 dB without using any dual-loop structure or introducing any long fiber to the OEO loop.

The schematic diagram of the proposed polarization-maintained COEO, incorporating a length of unpumped

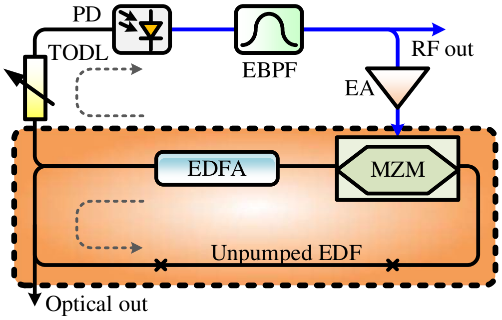

Fig. 1. Schematic diagram of the proposed polarization-maintained COEO incorporating a short length of unpumped EDF. EDFA, erbium-doped fiber amplifier; OC, optical coupler.

EDF, is shown in Fig. 1, which consists of an OEO and a mode-locked fiber laser sharing an electro-optical Mach–Zehnder modulator (MZM) and an EDF amplifier (EDFA). In the OEO, a photodetector (PD) is used to realize the optical-to-electrical conversion, and the converted electrical signal is filtered by an electrical bandpass filter (EBPF), amplified by an electrical amplifier (EA), and then led to the RF port of the shared MZM. The MZM is biased at the quadrature transmission point, which serves as the mode-locking device in the mode-locked fiber laser. A tunable optical delay line (TODL) is inserted to adjust the length of OEO loop so that the two loops can match with each other.

To suppress the undesired supermodes in the mode-locked fiber laser, a length of unpumped EDF is inserted. Thanks to the saturable absorption, the main modes that have large optical powers would saturate the unpumped EDF and lead to a reduced transmission loss, while the competing modes with low power cannot saturate the unpumped EDF and therefore experience a relatively large cavity loss. For fiber lasers, even a very small cavity loss difference between the oscillating modes could be accumulated to form a large output power difference, because the optical signal would circulate in the cavity for thousands of or even infinite times. In addition, the small reflections in the laser cavity could form standing waves in the unpumped EDF, which would generate the SHB effect. The SHB in the EDF would make the refractive index of the EDF changes spatially and further form a self-induced weak grating. The filtering characteristic of the self-induced weak grating affects the selection from the competitive modes in the mode-locked fiber laser cavity and further helps the suppression of the competing modes[13,15–17]. On the other hand, the suppression of the undesired supermodes would improve the phase noise performance of the generated RF signal. One key reason is that different groups of the supermodes have the same frequency spacing but different and unlocked phases. The beating of the supermodes in each supermode group would contribute to the generation of the desired RF signal. However, the random phases between the beating notes generated by different supermode groups will introduce phase noise degradation to the RF signal from the OEO loop.

An experiment based on the setup shown in Fig. 1 is carried out. The parameters of the key components are as follows: the MZM (FTM7938EZ) has a 3 dB bandwidth of 40 GHz; the PD has a 3 dB bandwidth of 10 GHz and a responsivity of 0.88 A/W; the gain of the low-noise EA is 27.5 dB over 9–11 GHz; the EBPF has a 3 dB bandwidth of 12.047 MHz centered at 9.999 GHz. To investigate the performance improvement caused by the unpumped EDF, several sections of unpumped EDF with three different absorption coefficients (7, 13, and 22 dB/m at 1530 nm) are applied. An optical spectrum analyzer (AQ6370C, 0.02 nm resolution) and a digital sampling oscilloscope (DSO, Agilent 86100C with module 86116C) are used to observe the optical spectra and the waveforms of the output optical pulses, respectively. In addition, a signal source analyzer (Rohde & Schwarz FSWP, 1 MHz–50 GHz) is used to analyze the electrical spectra and the phase noise performance of the generated RF signal in the OEO loop.

In order to evaluate the performance improvement of the polarization-maintained COEO via the unpumped EDF, 10 GHz optical pulse trains and RF signals are generated with and without introducing the unpumped EDF, respectively. Figure 2 shows the experimental results when the unpumped EDF is removed from the laser cavity. As can be seen from Fig. 2(a), the sidemode suppression ratio of the generated 10 GHz RF signal is 94.02 dB. This high sidemode suppression is mainly resulted from the relatively short lengths of the fiber laser cavity (~16 m) and the optoelectronic cavity (~32 m), which leads to large spacing between the sidemodes and makes them easily removed by the narrowband EBPF in the OEO loop. The waveform and optical spectrum of the generated optical pulses are shown in Fig. 2(b) and 2(c), respectively. The pulse width is about 7.6 ps, and the 3 dB bandwidth of the spectrum is about 0.672 nm. By directing the optical pulses into a PD, we can obtain the supermode suppression performance from the electrical spectrum. As shown in Fig. 2(d), the supermode suppression ratio is 52.4 dB, which is not satisfactory as compared with that in Refs. [15,16].

Then, a length of unpumped EDF is inserted into the laser cavity. Although the saturable absorption and SHB effect in the unpumped EDF could suppress the undesired supermodes, the length of the fiber laser cavity is increased, which may have an adverse effect on the suppression of the sidemodes of the generated RF signal, since the sideband spacing is shortened. Thus, an investigation on the effect of the length of the unpumped EDF on the sidemode suppression of the generated RF signal is performed. To do so, unpumped EDFs with an absorption coefficient of 13 dB/m at 1530 nm with lengths of 1, 2, and 4 m are incorporated into the laser cavity, respectively. Figure 3 shows the corresponding electrical spectra of the generated RF signals from the OEO loop. As can

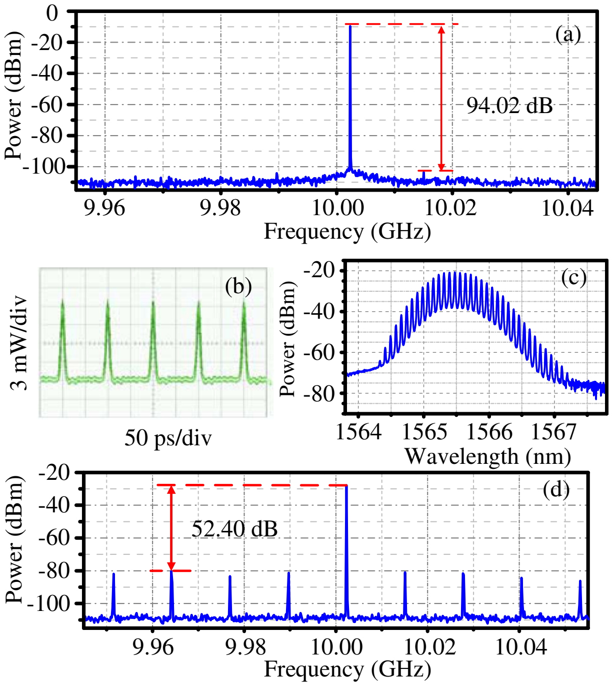

Fig. 2. (a) Electrical spectrum of the generated 10 GHz RF signal and (b) the eye diagram; (c) the optical spectrum and (d) the electrical spectrum of the generated optical pulses from the polarization-maintained COEO without incorporating an unpumped EDF.

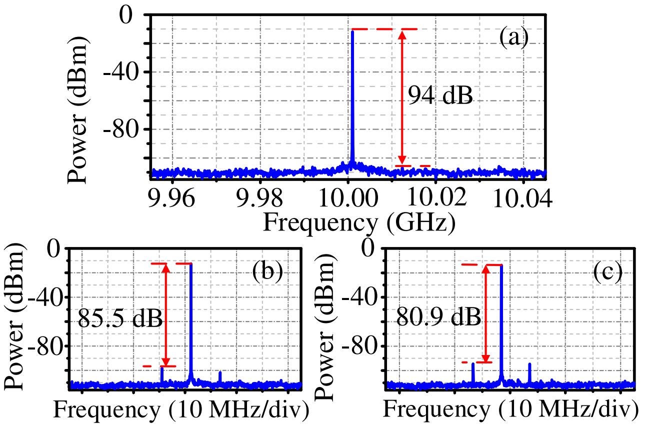

Fig. 3. Electrical spectra of the generated 10 GHz RF signal from the polarization-maintained COEO incorporating a (a) 1, (b) 2, or (c) 4 m unpumped EDF with an absorption coefficient of 13 dB/m at 1530 nm.

be seen, by using a 1 m EDF, the sidemode suppression ratio is kept at 94 dB, while for the 2 and 4 m EDF conditions, the sidemode suppression ratio is decreased to 85.5 and 80.9 dB, respectively. It can be seen that an optimized length of the EDF exists. This is because, on one hand, the EDF should have enough length to form the required SHB effect and the absorption effect to suppress the undesired modes. On the other hand, the EDF should not be too long to avoid increasing the length of the fiber laser loop and further shorten the mode spacing too much, which will adversely affect the undesired modes suppression. Thus, in the later experiment, the length of EDF is fixed at 1 m to make the system performance optimized.

The influence of the absorption coefficient of the unpumped EDF is also investigated. In this case, unpumped EDFs with three absorption coefficients (7, 13, and 22 dB/m at 1530 nm) are used. Figure 4 shows the electrical spectra of the optical pulses. For COEOs incorporating the three kinds of EDFs, the supermode suppression ratios are 60.6, 61.8, and 59.0 dB, respectively. Compared with the result in Fig. 2(d), which does not incorporate any unpumped EDF, the supermode suppression ratio is improved by 8.2, 9.4, and 6.6 dB, respectively. Thus, by incorporating a 1 m unpumped EDF with an absorption coefficient of 13 dB/m at 1530 nm, an optimized performance of the COEO is obtained. This indicates that the absorption coefficient of the unpumped EDF for the COEO is not a case of the larger the better. On one hand, if the absorption coefficient is too large, the optical power in the fiber laser will be greatly decreased, and, therefore, the system performance is deteriorated. On the other hand, weak saturable absorption is sufficient to guarantee significant suppression of the undesirable low power modes and noise, because the number of the optical and RF competing modes is reduced by the short cavity. In addition, the EDFs used in the experiments are not polarization-maintained. When the length of the EDF is shorter, the environment effect with the light polarization in the EDF will be weaker, which will make the system performance better. Thus by using the 1 m EDF, the environment effect with the polarization state is weaker than

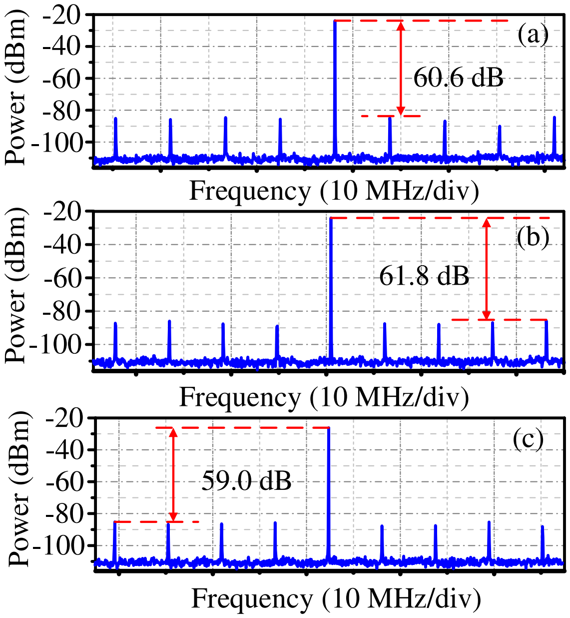

Fig. 4. Electrical spectra of the optical pulses when a 1 m EDF with absorption coefficients of (a) 7, (b) 13, or (c) 22 dB/m at 1530 nm is inserted to fiber laser cavity.

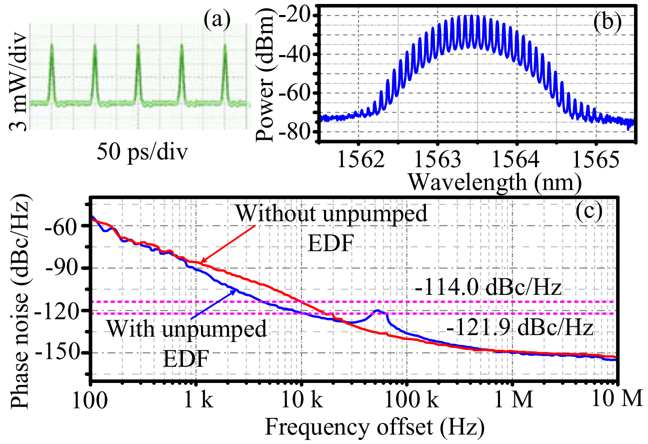

Fig. 5. (Color online) (a) Eye diagram and (b) optical spectrum of the generated optical pulse when 1 m EDF with an absorption coefficient of 13 dB/m at 1530 nm is incorporated; (c) the phase noise of the generated RF signal from the OEO loop with and without the 1 m EDF with an absorption coefficient of 13 dB/m at 1530 nm.

by using longer EDFs. In addition, if a polarization-maintained EDF is used in the loop, the system performance will be further improved.

Figures 5(a) and 5(b) show the eye diagram and the optical spectrum of the generated optical pulse train, respectively, when the 1 m EDF with an absorption coefficient of 13 dB/m at 1530 nm is incorporated. The pulsewidth is about 6.8 ps, which approaches the pulsewidth measurement limit of the DSO, and the 3 dB bandwidth of the spectrum is about 0.696 nm. The phase noise of the generated 10 GHz RF signal is also measured, as shown in Fig. 5(c), where the phase noise without using an unpumped EDF is also shown as a comparison. As can be seen, an improvement of 7.9 dB is realized for the phase noise at 10 kHz (i.e., from −114.0 to −121.9 dBc/Hz) by the unpumped EDF. In our experiments, EDFs with three different lengths are used, and 1 m is the experimental optimized length among these three conditions.

In conclusion, a polarization-maintained COEO incorporating an unpumped EDF in the laser cavity is proposed and demonstrated. An optical pulse train at a repetition rate of 10 GHz and a high quality 10 GHz RF signal are successfully generated. The supermode suppression ratio is improved by 9.4 dB, and the phase noise of the generated RF signal is improved by 7.9 dB, while the sidemode suppression ratio stays unchanged. The proposed scheme features a compact structure, simple operation, simultaneous high quality RF signal, and short optical pulse generation capability, which can find applications in photonics-based radar and satellite payloads.

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