Sidemode suppression for coupled optoelectronic oscillator by optical pulse power feedforward

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Abstract: Multiple sidemodes have been observed in a coupled optoelectronic oscillator (COEO) when the contained actively mode-locked fiber ring laser employs erbium-doped fiber (EDF). We propose that such sidemodes can be suppressed significantly by an optical pulse power feedforward scheme, through which the mode-locked optical pulse is reversely intensity-modulated by itself, resulting in a fast power limiting. Experimentally we show that sidemodes are suppressed as much as 40 dB in a 10-GHz COEO. The additional noise induced by the power feedforward technique is analyzed numerically. We show that for a COEO with a typical cavity length, the feedforward contribution to final single-side band (SSB) noise is minor and neglectable.

OCIS codes: (130.0250) Optoelectronics; (350.4010) Microwaves.

References and links

1. X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," J. Opt. Soc. Am. B **13**(8), 1725–1735 (1996).
2. A. J. Seeds and K. J. Williams, "Microwave photonics," J. Lightwave Technol. **24**(12), 4628–4641 (2006).
3. L. Maleki, "The optoelectronic oscillator," Nat. Photonics **5**(12), 728–730 (2011).
4. D. Eliyahu, D. Seidel, and L. Maleki, "Phase noise of a high performance OEO and an ultra-low noise floor cross-correlation microwave photonic homodyne system," in Proceedings of IEEE Conference on Frequency Control Symposium (IEEE, 2008), pp. 811–814.
5. D. Eliyahu and L. Maleki, "Low phase noise and spurious level in multi-loop opto-electronic oscillators," in Proceedings of IEEE Conference on Frequency Control Symposium (IEEE, 2003), pp. 405–410.
6. A. A. Savchenkov, V. S. Ilchenko, J. Byrd, W. Liang, D. Eliyahu, A. B. Matsko, D. Seidel, and L. Maleki, "Whispering-gallery mode based opto-electronic oscillators," in Proceedings of IEEE Conference on Frequency Control Symposium (IEEE, 2010), pp. 554–557.
7. I. Ozdur, D. Mandridis, N. Hoghooghi, and P. J. Delfyett, "Low noise optically tunable opto-electronic oscillator with Fabry-Perot etalon," J. Lightwave Technol. **28**(21), 3100–3106 (2010).
8. N. Yu, E. Salik, and L. Maleki, "Ultralow-noise mode-locked laser with coupled optoelectronic oscillator configuration," Opt. Lett. **30**(10), 1231–1233 (2005).
9. D. Eliyahu and L. Maleki, "Modulation Response (S21) of the Coupled Opto-Electronic Oscillator," in Proceedings of IEEE Conference on Frequency Control Symposium (IEEE, 2005), pp. 850–856.
10. A. E. Siegman, *Lasers* (Mill Valley, CA: University Science Books, 1986), Chap. 5.
11. G. T. Harvey and L. F. Mollenauer, "Harmonically mode-locked fiber ring laser with an internal Fabry-Perot stabilizer for soliton transmission," Opt. Lett. **18**(2), 107–109 (1993).
12. A. B. Matsko, D. Eliyahu, P. Koonath, D. Seidel, and L. Maleki, "Theory of coupled optoelectronic microwave oscillator I: expectation values," J. Opt. Soc. Am. B **26**(5), 1023–1031 (2009).
13. A. B. Matsko, D. Eliyahu, and L. Maleki, "Theory of coupled optoelectronic microwave oscillator II: phase noise," J. Opt. Soc. Am. B **30**(12), 3316–3323 (2013).
14. C. R. Doerr, H. A. Haus, E. P. Ippen, M. Shirasaki, and K. Tamura, "Additive-pulse limiting," Opt. Lett. **19**(1), 31–33 (1994).
15. M. Nakazawa, K. Tamura, and E. Yoshida, "Supermode noise suppression in a harmonically mode-locked fiber laser by selfphase modulation and spectral filtering," Electron. Lett. **32**(5), 461–463 (1996).
16. J. S. Wey, J. Goldhar, and G. L. Burdge, "Active harmonic modelocking of an erbium fiber laser with intracavity Fabry–Perot filters," J. Lightwave Technol. **15**(7), 1171–1180 (1997).
17. N. Onodera, "Supermode beat suppression in harmonically mode-locked erbium-doped fiber ring lasers with composite cavity structure," Electron. Lett. **33**(11), 962–963 (1997).

#247514 Received 7 Aug 2015; revised 26 Sep 2015; accepted 8 Oct 2015; published 12 Oct 2015

18. R. Wang, K. Xu, Y. Dai, F. Yin, J. Li, Y. Ji, and J. Lin, "Supermode noise suppression in an actively mode-locked fiber laser with pulse intensity feed-forward," in Proceedings of CLEO: 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper CM1I.2.
19. K. Xu, R. X. Wang, Y. T. Dai, F. F. Yin, J. Q. Li, Y. F. Ji, and J. T. Lin, "Supermode noise suppression in an actively mode-locked fiber laser with pulse intensity feed-forward and a dual-drive MZM," Laser Phys. Lett. **10**(5), 055108 (2013).
20. K. K. Gupta, D. Novak, and H. Liu, "Noise Characterization of a regeneratively mode-locked fiber ring laser," IEEE J. Quantum Electron. **36**(1), 70–78 (2000).
21. E. Keysight Technologies, PXA X-Series Signal Analyzer *http://literature.cdn.keysight.com/litweb/pdf/5990-3952EN.pdf*
22. E. C. Levy, M. Horowitz, and C. R. Menyuk, "Modeling optoelectronic oscillators," J. Opt. Soc. Am. B **26**(1), 148–159 (2009).

1. Introduction

Optoelectronic oscillator (OEO) is one of the potential microwave oscillators which can output spectrally pure sinusoidal wave up to tens of GHz [1–3]. High performance microwaves are of prime importance in a wide range of scientific and technological fields, such as communications, navigation, radar and precise scientific measurements. The significant advantage of OEO over other direct generation technologies is that the required high quality factor (Q-factor) cavity can be constructed by cheap and low-loss, large-bandwidth optical fiber. At present, state-of-the-art OEO has a record low-phase-noise (−163 dBc/Hz @ 6 kHz offset) by 16-km fiber [4]. Besides, rapid development of optical fiber communications provides off-the-shelf broadband optoelectronic devices, including Mach-Zehnder modulator (MZM) and photo detector (PD), to build easily such high quality microwave source. However, optical fiber is filtering-less, so that long transmission results in multi-mode oscillation in a simple OEO. Since the mode spacing is in inverse proportion to cavity delay, several kilometers of fiber correspond to very narrow mode spacing around hundreds or tens of kHz. It is impossible for usual microwave filter to select one particular mode, so that mode hopping is usually observed which is undesirable for most applications. As a result, mode selection while maintaining its phase noise performance is a major challenge for OEO. Keeping original mode spacing, the wanted mode can be extracted by compound cavity [5] or ultra-high-Q optical cavity [6,7]. Currently the most feasible and effective approaches include the coupled OEO (COEO), where the pure, filtering-less fiber transmission is replaced by an actively mode-locked fiber ring laser [8]. Inside the looped cavity, the microwave, carried by a high repetition rate optical pulse train, circulates many times before output, so that the equivalent time delay is greatly extended under a limited fiber length [9]. Accordingly, the mode spacing can match the current available microwave filter, e.g. ~MHz at 10 GHz.

Despite the greatly shortened fiber, the actively mode-locked fiber laser itself is still a multimode cavity. The cavity fundamental frequency is usually a few MHz but the repetition rate of the pulse train is tens of GHz, so that the fiber ring laser is harmonically mode-locked under very high order, i.e. the cavity supports a large number of cavity modes spaced by the cavity fundamental frequency. Due to the active nature of fiber ring laser, all of the cavity modes, where the gain exceeds its loss, are ready to oscillate. Correspondingly, one may observe many oscillation frequencies (the so-called sidemodes) around the wanted one, so that large amplitude noise appears within high offset frequency range of the laser [10,11] as well as of COEO. The employment of semiconductor optical amplifier (SOA) has been demonstrated by previous COEO reports. Its fast saturation results in different gain on each individual optical pulse, which helps the suppression of such high-frequency amplitude noise [12,13]. However, if the gain medium is erbium-doped fiber (EDF), the relaxation time of the erbium ions is much longer (~milliseconds) than the period of optical pulse train, so that all pulses experience the same gain, and the gain saturation cannot uniformly stabilize the energy amongst all pulses, resulting in significant sidemodes [14,15]. Since the EDF has advantages, including low noise figure and high saturated output power, over SOA, an effective way to suppress the corresponding COEO sidemodes is then desired.

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Various techniques have been reported to minimize the sidemodes inside an actively mode-locked EDF laser, for example, incorporation of a comb filter whose channel spacing is equal to the desired harmonic frequency [16], employment of a composite cavity structure [17], etc. Some fast power limiting mechanisms have also been demonstrated, based on the nonlinearity of the fiber, including nonlinear polarization rotation (NPR) followed by polarizer, or self-phase modulation (SPM) followed by spectral filtering [14,15]. In this paper, we propose and demonstrate experimentally a simple optical-power-feedforward-based power limiting scheme for COEO sidemode suppression. In hardware, only a PD and a broadband electronic amplifier are additionally used. Optical pulse train is firstly opto-electronic converted by a broadband receiver, and then fed forward to the in-cavity MZM where the pulse train is modulated by the reversed intensity profile of itself. A fast power limiting is then obtained by the proposed optical power feedforward [18,19]. Experimentally, an EDF-based COEO oscillating at 10 GHz is demonstrated. Under the fiber loop length of around 200 meters, no sidemodes are observed within the whole spectrum, 40 dB lower than that without feedforward. The measured single-side band (SSB) noise at 10-kHz offset frequency is lower than −125 dBc/Hz. The proposed COEO is also numerically studied, which shows that the feedforward path contributes little to the overall SSB noise. Feedforward performances under different saturation strength and delay mismatch are also discussed.

2. Experiment setup and result

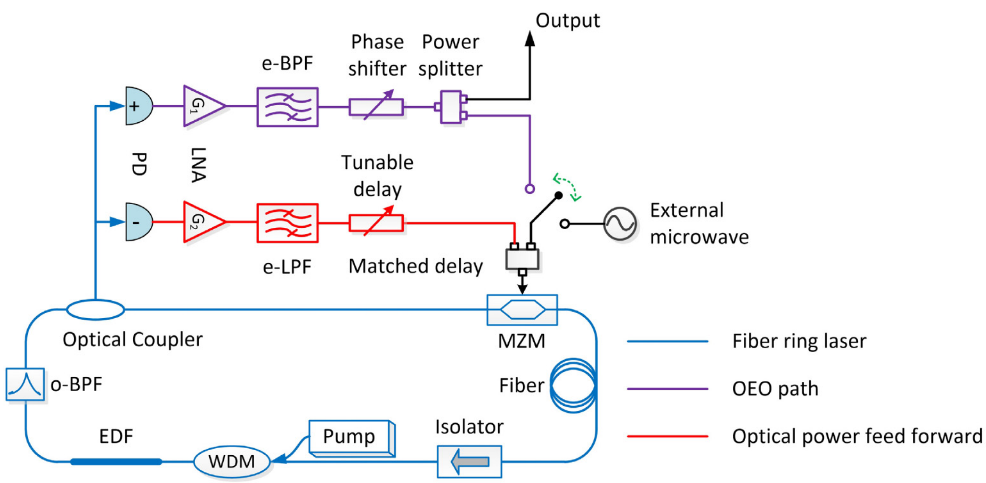

Fig. 1. The proposed COEO structure, as well as experiment setup, based on optical power feedforward technique. The red line shows the feedforward path. One can select mode-locked laser or COEO through the switch.

Figure 1 shows our experiment setup. The proposed COEO contains three parts: an actively mode-locked fiber ring laser, an OEO path, and a feedforward path. In fiber ring laser, the half-wave voltage (V_π) and intrinsical loss (besides the 3-dB loss due to quadrature bias) of MZM are 5 V and 3 dB around, respectively. The fiber is ~200 meters long. The optical amplifier is based on a 2.5-m EDF, with a small signal gain (g_{ss}) of 13 dB. The 3-dB bandwidth of the optical bandpass filter (o-BPF) is 1 nm, and its insertion loss is 1 dB. 30% of the optical power is output by a coupler, which is then evenly received by two PDs. An additional polarization controller is employed inside the cavity. In the OEO path, the PD bandwidth is 20 GHz and responsivity is nearly 1 A/W. The gain of broadband low-noise amplifier (LNA), G_1, is 20 dB. The electronic bandpass filter (e-BPF), centered at 10 GHz, has a 3-dB bandwidth of 10 MHz. The feedforward path has a similar structure as OEO path expect its broadband and low-pass feature. The PD has the same parameters as the other one except its negative output, i.e. the feedforward PD converts the received optical pulse into a

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negative electronic one. The gain of broadband LNA (G_2) is 13 dB, and the 3-dB bandwidth of electronic low-pass filter (e-LPF) is 10 GHz. Note losses of e-BPF and e-LPF have been accounted into the gains of corresponding LNAs.

Here we show experimentally that sidemodes result from the active mode-locking. We drive the MZM by an external sinusoidal wave around 10 GHz, to emulate the sidemode-free COEO. Without the optical feedforward path, the spectrum of the generated pulse train is measured and shown in Fig. 2(a). Obvious sidemodes are observed, even if the driving frequency is carefully tuned to be exactly integrated number of the cavity fundamental frequency. Since the sidemodes are optically carried and generated inside the fiber cavity, they are not ready to be removed by the outside mode-selection microwave filter, i.e. by e-BPF in OEO path. Note that in our experiment (as well as that shown below) the fiber ring laser is simply placed under an ordinary laboratory condition, without temperature or vibration isolation. The cavity length is not actively stabilized, either. In such an environment sidemodes are unavoidable for an EDF-based laser, even if the regenerative mode-locked structure is employed [20].

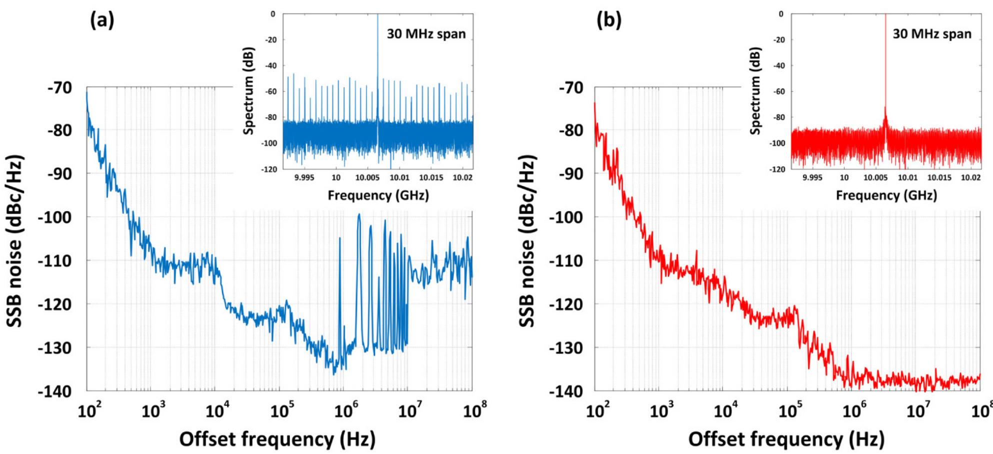

Fig. 2. (a) The measured SSB noise spectrum when the 200-m fiber ring laser is driven by an external ~10-GHz microwave tone without the feedforward path. Inset: the measured 30-MHz-span spectrum around the carrier; the resolution bandwidth (RBW) of the electronic spectrum analyzer is 3 kHz. (b) SSB noise spectrum with feedforward. Inset: 30-MHz-span spectrum.

In fiber cavity, superposition of sidemodes corresponds to intensity fluctuation on optical pulse train. Accordingly, in-loop optical power limiting can solve this problem: optical pulse with larger energy gets less gain than those with less energy, so that energies of all pulses will be uniformly stabilized after enough circulations. Here we employ the optical feedforward path to realize the above power clamping: the optical pulse is firstly converted to electronic pulse, which then modulates itself through MZM [19]. The power limiting stands under the following two implementations. Firstly, the delay of feedforward path is the same as that of optical path inside the fiber ring laser (i.e. from optical coupler to MZM in Fig. 1). In experiment, we select electronic cable with suitable length so that the delay of feedforward path is approximately equal to that of the fiber-cavity part. Then an electronic tunable delay line is used for fine tuning. Secondly, the feedforward PD converts the optical pulse to a negative electronic one, while the MZM is quadrature-biased on its positive transfer curve. As a result, each optical pulse reversely modulates itself, and the transmissivity gets less if its energy increases. One can expect that such power limiting has adjustable modulation depth and relaxation time according to the LNA gain and bandwidth of the e-LPF, respectively.

In [19] we have shown superb sidemode suppression of a 12.5-m-long actively mode-locked fiber laser based on the power feedforward technique, where the laser is harmonically mode-locked under order around 625. In a COEO, however, a much longer cavity is required in order to minimize its phase noise. Here the ~200-m fiber cavity results in much denser

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mode spacing ~1 MHz. When the feedforward is ON with optimized parameters, no obvious sidemodes are found as shown in Fig. 2(b). According to the SSB noise spectrum, the sidemode spurs are suppressed as much as 38 dB. Such fiber length is a typical value for COEO, and the optical power feedforward still shows effective sidemode suppression under such long cavity, i.e. under as large harmonics order as 10^4.

Replacing the external microwave source by OEO path, as shown in Fig. 1, one can then get a COEO. Here we tune a microwave phase shifter to phase synchronize the OEO path and fiber ring. With optimized feedforward strength, the microwave oscillation output is measured and shown in Fig. 3(a).

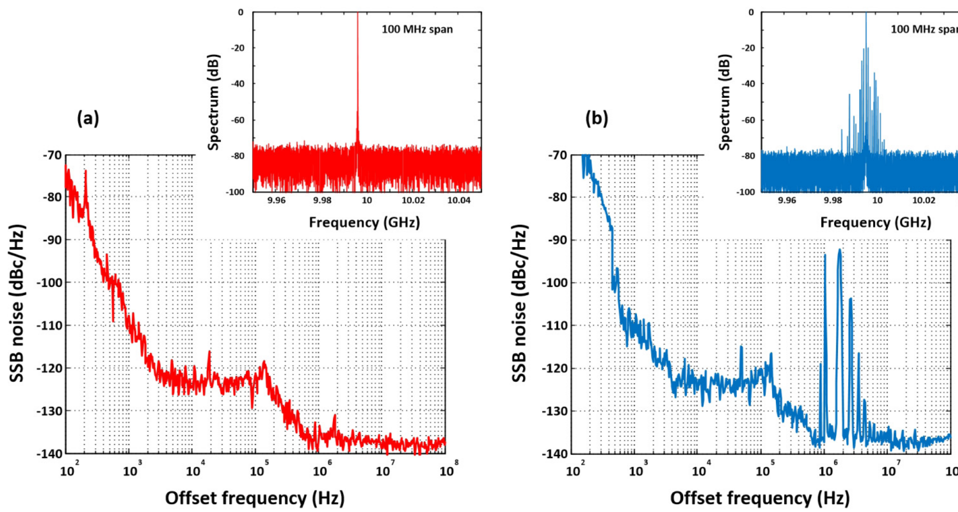

Fig. 3. (a) The measured SSB noise spectrum when COEO oscillates with feedforward path. Inset: the measured 100-MHz-span spectrum around oscillation carrier; the RBW is 3 kHz. (b) SSB noise spectrum without feedforward. Inset: 100-MHz-span spectrum.

The oscillation is at 9.996 GHz and the power is 12 dBm. Single mode operation is observed around 100 MHz span. As a comparison, oscillation when the feedforward path is OFF is measured and shown in Fig. 3(b). Obvious sidemodes with 1-MHz interval are found, corresponding to the 200-m fiber loop delay. The SSB noise spectrum is also measured. Figure 3(a) shows SSB noise around −125 dBc/Hz at 10-kHz offset frequency. A lower value is expected since it is also the noise floor of our Agilent N9030A [21]. The relatively high SSB noise around 100-kHz offset frequency reflects the equipment floor, too. Comparing the SSB noise spectrums in Figs. 3(a) and 3(b), one can find a lower noise below 1-kHz offset frequency, which may benefit from the stable single mode oscillation under feedforward. Without it, frequent mode hopping is found since the e-BPF bandwidth (10 MHz) is much larger than mode spacing (1 MHz). Almost the same SSB noises are found at higher offset frequency, except that the sidemodes are greatly suppressed (>40 dB). The result is consistent with the value obtained in the actively mode-locked laser in Fig. 2.

3. Simulation and discussion

A competent sidemode suppression method should meanwhile introduce neglectable SSB noise into the COEO output. Different from the sidemode which is at high offset frequency range, the SSB noise characterizes the low-offset-frequency noise of the generated microwave. Here we discuss the SSB noise performance as well as the sidemode suppression by numerical simulation. Parameters of all parts follow the experiment above. Others used in the simulation are listed below, which are also the estimations of devices we use. We assume all filters, the o-BPF, e-BPF, and e-LPF, have Gaussian-shape profile. The EDF amplifier has a saturated power (P_{sat}) of 5 dBm, so that its gain saturation (g) is described as $g = g_{ss}/(1 +$

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P_{ave}/P_{sat}), where P_{ave} is the in-loop average power. The noise figure is 4 dB. Noise figure of the OEO LNA is 5 dB, while it is 11 dB for the feedforward LNA. Both thermal and shot noises are considered in PDs. Phase synchronization of the OEO path stands automatically at the wanted microwave tone ~10 GHz. The COEO follows the mathematical model described in [22]. Both optical and electronic fields start from noise, and then are iterated until the fields become constant after a finite number of traversals of the whole cavity.

When the feedforward path is perfectly delay matched, a simulation is firstly run to evaluate the sidemode suppression and possible SSB noise degradation. Figure 4(a) shows the superb sidemode suppression clearly: within 10-MHz offset band, the sidemodes are suppressed around 140 dBc/Hz. Such suppression agrees well with the experiment result in Fig. 3(a).

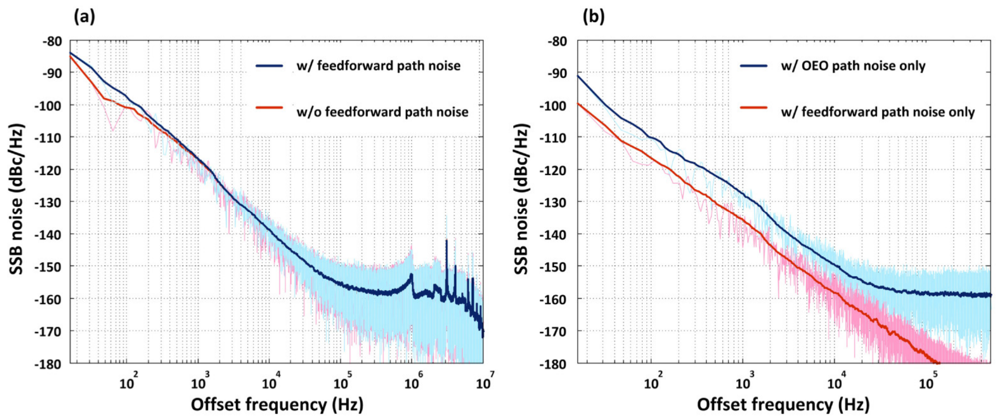

Fig. 4. Simulated SSB noise spectrums of COEO under optical power feedforward. (a) Blue line: all noises are considered; red line: the noise from feedforward path is ignored. (b) Blue line: only the noise from OEO path is considered; red line: only the noise from feedforward path is considered.

Meanwhile, the typical SSB noise at 10-kHz offset frequency approaches −140 dBc/Hz under the above parameters. The possible additional noise induced by feedforward is analyzed by two comparison simulations. Firstly, in feedforward path, we ignore the noises from both PD and LNA. Other noises (those from fiber ring laser and from OEO path) are considered as above. The resulted SSB noise spectrum is shown in Fig. 4(a). With or without the noise of feedforward path, no significant SSB noise performance change is observed at the final output. Such result can be understood as follows. As shown in Fig. 1, the outputs both from feedforward path and from OEO path are power combined together and fed into the MZM, so that both noises can be considered to contribute to the final SSB noise in a similar way. However, their noise power densities are different. The average optical power hitting on each PD is around 6.5 dBm. Though the LNA in feedforward path (a 10 Gb/s optical modulator driver from JDS Uniphase is actually used) has noise 6 dB larger than that in OEO path, the overall equivalent input noise density (after considering the shot noise of PD) before the feedforward LNA is only 2.5 dB higher. After the two LNA and filter sets with different gain (10 dB at 10 GHz), the output noise density of feedforward path is actually 7.5 dB (at 10 GHz) lower than that of OEO path. The above numbers show that the feedforward path at least contributes less to final SSB noise than OEO path. We run a second comparison simulation where only the noise from feedforward path and that from OEO path are considered, respectively, while others (including that of fiber ring laser) are ignored. Figure 4(b) shows their individual contributions to the final SSB noise. The OEO path contributes nearly 10 dB higher than feedforward path. This simulation explains the comparison in Fig. 4(a), from which we conclude in current design, the output noise of feedforward path is less than that from OEO path, so that its contribution to final SSB noise is minor.

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Note in Fig. 1, the OEO path and feedforward path constitute a two-tap photonic microwave filter, which however has no contribution to sidemode suppression. Actually, at oscillation frequency the two filter branches have exactly opposite phase before their combination, so that the oscillation carrier experiences the minimum transmission of the 2-tap filter. Since the power limiting has the credit, one can tune G_2 to control the limiting strength, and the sidemodes change accordingly. We find, both in simulation and in experiment, there is a threshold G_2 beyond which the sidemodes can be suppressed as the same and good performance as shown in Figs. 4(a) and 3(a); once G_2 is less than the threshold, large sidemodes appear. In experiment, we estimate the threshold gain around 10 dB. Though any larger G_2 works, excessive power limiting is not recommended. On one hand, the two-tap filter shows loss on the oscillation. In current design such loss is small due to the large gain difference between the feedforward and OEO path (10 dB). Excessive G_2 results larger loss. On the other hand larger G_2 also results in larger feedforward noise as well as the SSB noise contribution. For example, when G_2 is 18 dB the SSB noise contribution from the feedforward path only is shown in Fig. 5(a).

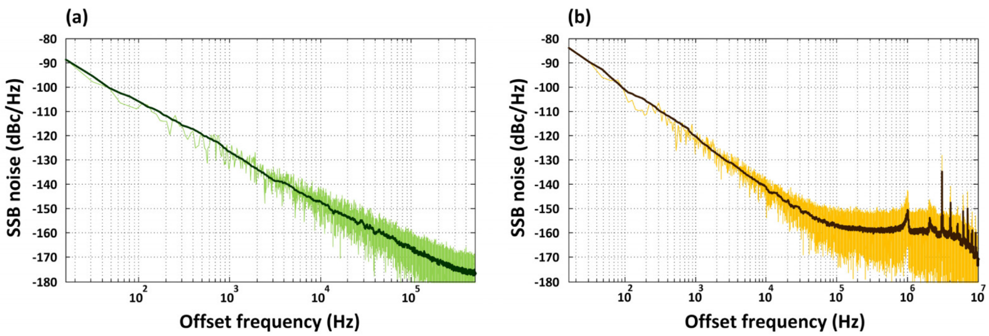

Fig. 5. (a) Simulated SSB noise contribution from feedforward path only with enlarged G_2. (b) Total SSB noise with 10-ps feedforward delay mismatch.

Compared with Fig. 4(b), noise contribution is enlarged and now is equal to that from OEO path. But the sidemodes have already been well suppressed as Fig. 4(a). Based on the above analysis, the optimal G_2 should be slightly larger than the threshold. Besides, one can expect that sidemode suppression and additional SSB noise may be a trade off if the fiber ring length is further extended.

"ON/OFF-like" sidemode suppression is also observed when the feedforward delay is mismatched. Experimentally we find the same SSB noise spectrum as Fig. 3(a) when the feedforward delay is tuned within around ± 10 ps range. Corresponding simulation confirms this. Figure 5(b) shows SSB noise spectrum when delay mismatch is 10 ps. Little sidemode suppression degradation is found compared with Fig. 4(a). The optical pulse within cavity has duration around 15 ps; after feedforward path which contains the 10-GHz e-LPF, the electronic pulse for the further power limiting is enlarged to around 30 ps. This should be the reason why there is a ± 10-ps-around tolerance. The above two "ON/OFF-like" operations may be explained as follows. The sidemodes are also oscillations while the feedforward shows a loss. When the power limiting strength and delay mismatch are within their working ranges, such loss makes sure that the sidemode oscillations are under threshold with the same and weak power. However, small power limiting or large delay mismatch weakens the loss so that sidemodes oscillate. In our current setup the delay mismatch tolerance is ± 10 ps (± 3 millimeters in vacuum), which is easy to achieve in practice. Comparing Figs. 5(b) and 4(a), one can find SSB noise is not deteriorated, either, since the delay mismatch does not enlarge the noise of feedforward path. Note that in the OEO path the phase synchronization rather than delay match is required, that is, delays both of OEO path and of fiber ring should be integral numbers of microwave oscillation period. Such condition is required in all COEOs.

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4. Conclusion

In this paper the sidemode suppression in an EDF-based COEO was studied. The sidemodes are generated because of the long relaxation time of the erbium ions. Correspondingly, we proposed that a fast power limiting was able to suppress the sidemodes, which was obtained by the optical power feedforward technique. By inserting an additional PD and broadband electronic amplifier, the COEO sidemodes were suppressed as much as 40 dB. The SSB noise at 10-kHz offset frequency was below −125 dBc/Hz when the COEO oscillated at 10 GHz. The additional SSB noise was believed to be neglectable under a typical fiber length (~200 meters), since the numerical analysis showed that noise contributed by the feedforward path was much less than OEO path.

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