Stable and Frequency-Hopping-Free Microwave Generation Based on a Mutually Injection-Locked Optoelectronic Oscillator and a Dual-Wavelength Single-Longitudinal-Mode Fiber Laser

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***Abstract*—We report a novel method to generate a stable and frequency-hopping-free microwave signal based on a mutually injection-locked dual-wavelength single-longitudinal-mode fiber laser and an optoelectronic oscillator (OEO), with the mutual injection locking realized by sharing an optical path consisting of a polarization modulator and a polarization-maintaining phase-shifted fiber Bragg grating. The two wavelengths from the fiber laser are injected into the OEO to lock the generated microwave signal, while the microwave signal from the OEO is fed back into the fiber laser to injection lock the two wavelengths. Thanks to the mutual injection locking, the operation stability of the fiber laser and the OEO are substantially improved. A microwave signal at 11.8 GHz with a phase noise of −105 dBc/Hz at a 10-kHz offset frequency is generated. A stable operation of the system without frequency shifting and hopping is demonstrated.**

***Index Terms*—Erbium doped fiber amplifier, fiber Bragg gratings, fiber laser, injection locking, microwave, optoelectronic oscillator (OEO), phase shift, single longitudinal mode.**

I. Introduction

MICROWAVE signal generation using an optoelectronic oscillator (OEO) [1] or by heterodyning two wavelengths from a dual-wavelength single-longitudinal-mode (DW-SLM) fiber ring laser (FRL) [2] has been considered two effective solutions for the generation of a high-frequency and ultra-low phase noise microwave signal, and can find important applications such as in radar, optical and wireless communications, microwave imaging, and modern instrumentation [3], [4]. For both an OEO and a FRL, to reduce the phase noise, a simple solution is to increase the loop length. However, an OEO or a FRL with a long loop will have a large number of densely-spaced oscillation modes, which would cause severe frequency hopping, making it difficulty to maintain a stable and frequency-hopping-free operation [1], [5].

For an OEO, to ensure single mode operation, a high-Q microwave bandpass filter (BPF) is required. To ease such a requirement, a solution is to use multiple fiber loops in an OEO [6] to make the mode spacing greater. The major limitation of using multiple loops is that the system is complicated and the stability is poor. Another solution is to use a high-Q optical filter, such as a phase-shifted fiber Bragg grating (PS-FBG) [7] or a whispery-gallery-mode (WGM) resonator [8], to equivalently obtain a high-Q photonic microwave BPF in an OEO. However, FBGs and WGM resonators are very sensitive to environmental disturbance, giving rise to poor frequency stability. Mutual injection locking (MIL) between two independent OEOs with different loop lengths is another solution to realize stable operation without frequency hopping [9]. However, the complexity and the cost are greatly increased.

For a DW-SLM fiber laser, if the gain medium is an erbium-doped fiber, due to the strong homogenous line broadening, mode hopping is a serious issue which makes the operation of the fiber laser very instable. To suppress mode hopping, an optical filter with two ultra-narrow bands, such as a multi-ring cavity filter [10], a PS-FBG [11], a saturable absorber [12], or a fiber micro-disk resonator [13], can be used to select only two modes. The major limitation is the limited frequency tunability. To reduce the mode hoping, we may use a gain medium having less homogenous line broadening, such as a semiconductor optical amplifier (SOA) in the ring cavity [14]. But the relatively high noise of an SOA makes the generated microwave signal have poor noise performance. The use of the stimulated Brillouin scattering (SBS) gain in a fiber laser is another solution to reduce mode hopping [15]. To trigger the SBS, however, a high optical pump power is needed.

In this paper, we propose and demonstrate, for the first time to the best of our knowledge, a mutually injection-locked OEO and DW-SLM fiber laser for stable and frequency-hopping-free microwave generation. The mutually injection-locked OEO and DW-SLM fiber laser share an optical path consisting of a polarization-maintaining PS-FBG (PM-PS-FBG) and a polarization modulator (PolM). Two orthogonally polarized wavelengths generated in the fiber laser are injected into the OEO to lock the generated microwave signal, which is then applied to the PolM to re-lock the two wavelengths in the fiber laser. Thanks to the MIL, a stable microwave signal that is free of frequency-hopping is generated. The phase noise performance of the generated microwave signal due to the MIL is also improved. The proposed technique is evaluated by an experiment. A stable 11.8-GHz microwave signal that is frequency-hopping

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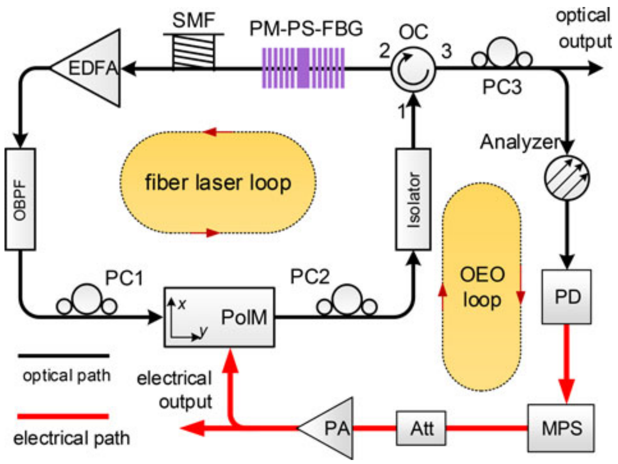

Fig. 1. Schematic of the mutually injection-locked OEO and DW-SLM fiber laser.

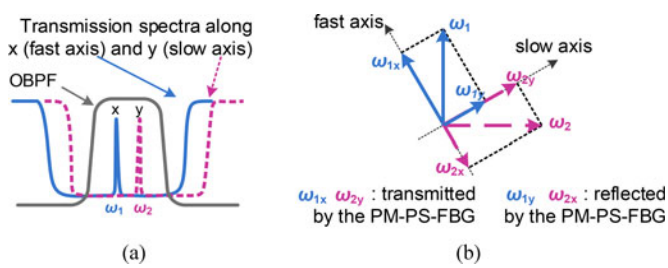

Fig. 2. (a) Transmission spectra of the OBPF and the PM-PS-FBG; (b) misalignment between the orthogonal polarization directions of $\omega 1$ and $\omega 2$ in the fiber laser and the fast and slow axes of the PM-PS-FBG.

free is generated. The phase noise of the microwave signal is -105 dBc/Hz at a 10-kHz offset frequency.

II. Principle of Operation

The schematic of the proposed mutually injection-locked OEO and DW-SLM fiber laser is shown in Fig. 1. The system consists of two mutually locked subsystems, an OEO and a DW-SLM fiber laser, which share an optical path consisting of a PolM and a PM-PS-FBG.

A. Dual-Wavelength SLM Fiber Laser

The DW-SLM fiber laser consists of an erbium-doped fiber amplifier (EDFA), a single-mode fiber delay line, two polarization controllers (PC1 and PC2), an optical isolator, a PolM, an optical BPF (OBPF), an optical circulator (OC), and a PM-PS-FBG. The isolator is used to ensure that the light wave in the fiber laser circulates along the counterclockwise direction only. As shown in Fig. 2(a), due to the birefringence of the polarization-maintaining fiber (PMF) used to fabricate the PM-PS-FBG, there are two spectrally separated ultra-narrow transmission bands along the fast and slow axes of the grating, which are selected by the OBPF for orthogonally polarized dual-wavelength oscillation. The EDFA in the loop is used to provide a gain to compensate for the loss in the loop to support the dual-wavelength oscillation. The PolM is a special phase modulator that supports phase modulation with complementary modulation indices along the two principal axes (x and y in Fig. 1) [16]. Assuming that the two wavelengths along the x and the y axes are aligned with the fast and slow axes, respectively, by adjusting PC1; the x or the fast axis, and the y or the slow axis are set as the two basic reference directions. In addition, the oscillating wavelengths are denoted as $\omega_{1\mathrm{x}}$ and $\omega_{2\mathrm{y}}$, indicating the two wavelengths along the fast axis (x-axis) and slow axis (y-axis). The PM-PS-FBG can be considered as two independent sub-PS-FBGs, $\mathrm{PS-FBG_x}$ and $\mathrm{PS-FBG_y}$, with a transmission band along its fast and slow axes, respectively. Typically, the length of the fiber loop could be as long as hundreds of meters, giving a mode spacing in an order of kHz. Considering that the transmission band of a sub-PS-FBG is in the order of about tens of MHz [17], mode competition leading to mode hopping will happen for the wavelengths along the two polarization directions. To ensure stable long-term operation, an additional mechanism to suppress mode hopping must be employed. A solution is to use the proposed MIL.

To couple partially the two wavelengths generated by the fiber laser to the OEO to achieve MIL, the polarization directions of two wavelengths are controlled by tuning PC2 to be not fully aligned with the principal axes of the PM-PS-FBG so that only part of the light waves at $\omega_{1\mathrm{x}}$ and $\omega_{2\mathrm{y}}$ will transmit through the PM-PS-FBG, and the other part at $\omega_{1\mathrm{y}}$ and $\omega_{2\mathrm{x}}$ will be reflected by the PM-PS-FBG and coupled into the OEO via port 3 of the OC, as illustrated in Fig. 2(b).

B. Optoelectronic Oscillator

The OEO shares the PolM and the PM-PS-FBG with the fiber laser. Two other components, PC2 and the OC, are also in the shared path. In addition to the shared components, the OEO also has an additional PC (PC3), a polarization analyzer (PolA), a photodetector (PD), a microwave phase shifter (MPS), an attenuator (ATT), and a power amplifier (PA). The coupled light waves at $\omega_{1\mathrm{y}}$ and $\omega_{2\mathrm{x}}$ will pass through the polarization analyzer to project the two wavelengths to one polarization direction, and be detected at the PD. The generated signal, after passing through the MPS, the ATT and the PA, is applied to the PolM, to close the OEO loop.

To understand the operation of the OEO, we first study the spectral response of the OEO. Assume that the fiber laser is disconnected at the EDFA, and the coupled light waves at $\omega_{1\mathrm{y}}$ and $\omega_{2\mathrm{x}}$ from port 3 of the OC are equivalently treated as external incident light waves from the input port of the PolM and reflected by $\mathrm{PS\text{-}FBG_y}$ and $\mathrm{PS\text{-}FBG_x}$. Then, we disconnect the OEO at the output of the PD. The PolM, the PM-PS-FGBG, the PolA and the PD form a microwave photonic (MWP) filter thanks to phase-modulation to intensity-modulation conversion [18]. For the optical wavelength from the PM-PS-FBG at $\omega_{1\mathrm{y}}$, the MWP filter has a passband at $\omega_{2\mathrm{y}} - \omega_{1\mathrm{y}}$, and for the optical wavelength at $\omega_{2\mathrm{x}}$, the MWP filter has a passband at $\omega_{2\mathrm{x}} - \omega_{1\mathrm{x}}$, both are located at the same location (denoted as $\omega_2 - \omega_{1)}$, as shown in Fig. 3. The 3-dB bandwidth of the MWP filter is determined by the notch width of the PM-PS-FBG, which is typically in the

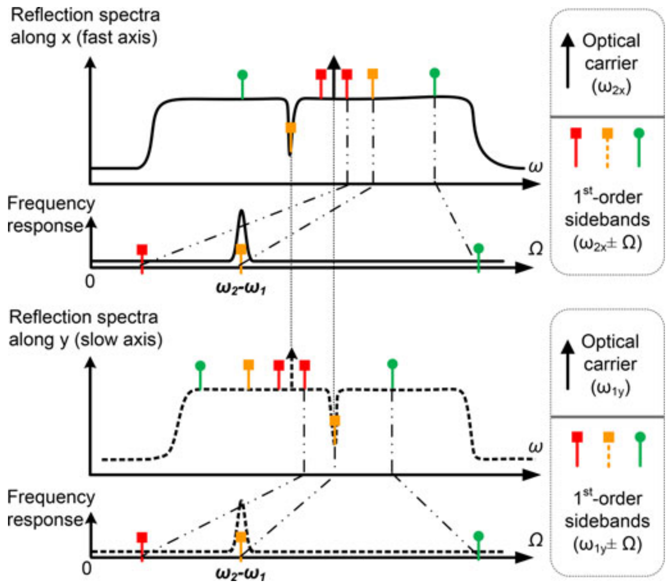

Fig. 3. The illustration of the formation of two equivalent MPBPFs. Upper: the MPBPF based on $\omega_{2\mathrm{x}}$ and PS-FBGy; lower: the MPBPF based on $\omega_{1\mathrm{y}}$ and PS-FBGx.

range of tens of MHz. More details about the operation of the MWP filter can be found in [18]. Since the OEO loop has an equivalent MWP filter, if the gain is greater than the loss, when the loop is closed, the OEO will start to oscillate. The generated microwave signal is coupled to the DW-SLM fiber laser via the PolM.

C. Mutual Injection Locking

Then we study the MIL between the OEO and the DW-SLM fiber laser. When both the OEO and the fiber laser start oscillation, the two wavelengths at $\omega_{1\mathrm{x}}$ and $\omega_{2\mathrm{y}}$ generated by the fiber laser will be phase-modulated by the microwave signal at $\omega_2 - \omega_1$ generated by the OEO. Each wavelength produces two more sidebands at the output of the PolM: $2\omega_{1\mathrm{x}} - \omega_{2\mathrm{x}}$, and $\omega_{2\mathrm{x}}$ for $\omega_{1\mathrm{x}}$; $2\omega_{2\mathrm{y}} - \omega_{1\mathrm{y}}$ and $\omega_{1\mathrm{y}}$ for $\omega_{2\mathrm{y}}$. All the wavelengths pass through PC2 and sent to the PM-PS-FBG. Since the polarization directions of two wavelengths are not fully aligned with the principal axes of the PM-PS-FBG by tuning PC2, each wavelength will be split into two light waves along the two orthogonal axes. Among these light waves, the wavelengths at $\omega_{1\mathrm{y}}$ and $\omega_{2\mathrm{x}}$ are reflected by the PM-PS-FBG and routed to the PD via the OC to injection lock the OEO; while the wavelengths at $\omega_{1\mathrm{x}}$ and $\omega_{2\mathrm{y}}$ are transmitted through the PM-PS-FBG. Note that thanks to the phase modulation at the PolM, one wavelength, say $\omega_{1\mathrm{x}}$, generates $\omega_{2\mathrm{y}}$ to injection lock the other wavelength $\omega_{2\mathrm{y}}$ in the fiber laser; and vice versa. Therefore, a wavelength with a higher power will introduce stronger injection locking to the other wavelength. Such a wavelength-coupling between $\omega_{1\mathrm{x}}$ and $\omega_{2\mathrm{y}}$, similar to the self-stabilizing effect of four-wave mixing in a multi wavelength fiber laser [19], would suppress the mode competition between the two orthogonally polarized wavelengths and ensure improved two-wavelength power stability. In addition, when mode hopping along each polarization

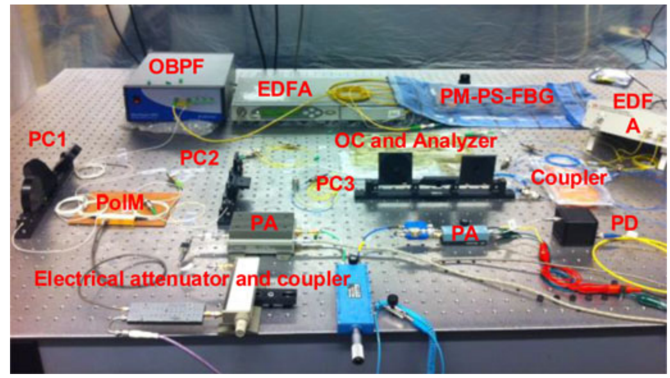

Fig. 4. Photograph of the experimental setup.

direction happens in the fiber laser, similar frequency hopping in the electrical domain in the OEO could also appear. However, by properly configuring the length and the gain of the OEO loop, undesired frequencies can be removed and only one frequency, $\omega_2 - \omega_1$ can maintain self-sustained oscillation. This frequency at $\omega_2 - \omega_1$ will lock the wavelength difference of the oscillation modes in the fiber laser, and accordingly alleviate the mode hopping in the DW-SLM fiber laser through wavelength-coupling introduced by the phase modulation at the PolM. Therefore, thanks to the MIL between the OEO and the DW-SLM fiber laser, both mode hopping and mode competition can be eliminated greatly.

The proposed setup seems like a regeneratively mode-locked laser [20], [21] and a coupled optoelectronic oscillator [22], [23] for all of them have an optical fiber loop and an optoeletronic loop and both loops as two oscillators can be coupled through injection locking. However, the proposed system is different from the previous methods: 1) without the opto-electronic loop, the optical fiber loop in the proposed setup can generate two orthogonally polarized SLM due to the PM-PS-FBG, while the previous methods can only generate a unstable CW light wave; 2) coupling between the optical loop and the opto-electronic loop in the proposed setup is achieved through fundamental injection locking instead of harmonic injection locking that is implemented in the previous setup; 3) the frequency of the generated microwave signal in the proposed method can be tuned by simply stretching or heating the PM-PS-FBG, while in the previous methods, it is determined by the electrical filter used in the opto-electronic loop, and usually fixed.

III. Experimental Results and Discussion

A. Experimental Setup

A mutually injection-locked OEO and DW-SLM fiber laser based on the setup shown in Fig. 1 is built, as shown in Fig. 4. The PolM (Versawave) has a bandwidth of 40-GHz. The PM-PS-FBG is fabricated in a PMF based on the phase-mask technique, by scanning an ultraviolet beam along the PMF by passing the beam through a uniform phase mask. A phase shift is introduced to the center of the fiber by moving the phase mask by half the

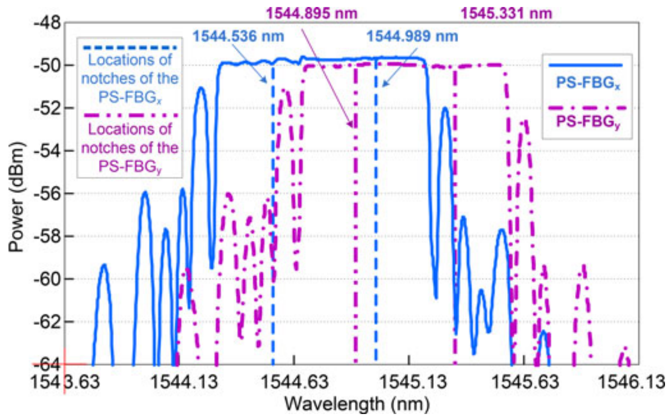

Fig. 5. Measured reflection spectral responses the PM-PS-FBG along its fast and the slow axis. (resolution: 0.01 nm).

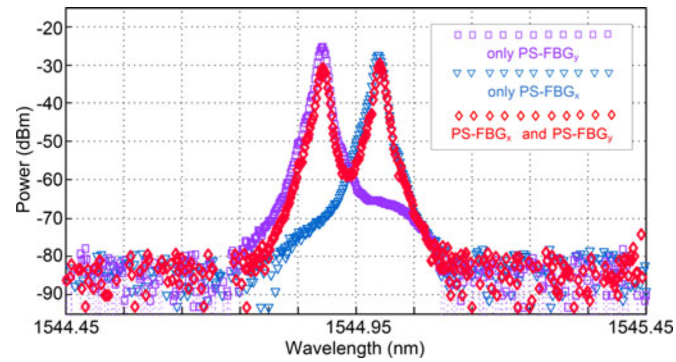

Fig. 6. Measured optical spectra of the output of the dual-wavelength fiber laser when it is configured at single wavelength and dual-wavelength operations.

corrugation, leading to a π phase shift. Thus, an ultra-narrow transmission band along one principal axis is produced.

The reflection spectra of the PM-PS-FBG along the two principal axes are measured by an optical spectrum analyzer (OSA, Ando AQ6317B), as shown in Fig. 5. The total reflection bandwidth for each band is about 0.9 nm. The transmission bands are ultra-narrow and cannot be observed due to the limited resolution (0.01 nm) of the OSA. However, based on phase to intensity modulation conversion [18], the locations of transmission bands can be precisely determined, which are indicated in Fig. 5. The 3-dB bandwidth of each transmission band is measured to be 0.3 pm, or 37 MHz, which is ultra-narrow. The OBPF is configured to select the transmission band at 1544.895 nm for PS-FBG$_y$ and the other at 1544.989 nm for PS-FBG$_x$ to achieve dual-wavelength oscillation. The wavelength spacing between the two transmissions bands is 0.094 nm, corresponding to a microwave frequency of 11.8 GHz. The PM-PS-FBG is placed in a lab-made container which is capable of isolating environmental vibrations, air flows and temperature drifts so that the long-term stability of the PM-PS-FBG can be ensured.

Inside the OEO, the two orthogonally polarized wavelengths reflected from the PM-PS-FBG are routed by the OC to the PolA, to project the two orthogonally polarized wavelengths to the principal axis of the PolA, and then sent to the PD (45 GHz, Newport) to generate a microwave beat note. The microwave signal at the output of the PD is applied to the PolM after passing through the MPS, the ATT, a low noise amplifier and a PA, to form the OEO loop.

B. Dual-Wavelength SLM Fiber Laser Without Mutually Injection Locking

First, the OEO is disconnected at port 3 of the OC. The output of the fiber laser is measured by the OSA at the output of port 3 of the OC, and shown in Fig. 6. By properly adjusting PC1 and PC2, the fiber laser can be configured at either single-wavelength oscillation at 1544.895 or 1544.989 nm or dual-wavelength oscillation at both wavelengths. The total fiber loop length is about 600 meters, giving rise to a 320 kHz mode spacing that is much smaller than the 3-dB bandwidth of the transmission bands of the PM-PS-FBG, which is about 37 MHz. Therefore, whether the fiber laser is configured at a single-wavelength or a dual-wavelength oscillation mode, mode competition and mode hopping could be observed.

By heterodyning two wavelengths around 1544.895 and 1544.989 nm, a microwave signal at about 11.8 GHz is generated. Since the mode competition and mode hopping in the optical domain are severe, the generated microwave signal also experiences strong frequency hopping, frequency shifting and power fluctuation, which is visualized and demonstrated by recording the electrical spectrum of the microwave signal at the output of the PD using an electrical spectrum analyzer (ESA, Agilent E4448A), for 20 min with a time interval of 60 s, as shown in Fig. 7(a).

C. Mutually Injection Locking

Then, the OEO is closed and the MIL is enabled. The power of the light waves sent to the PD is 1 dBm. The power of the microwave signal at the output of the PD is about -35 dBm, which is split into two paths: one is set to the PolM, the other one is sent to a signal source analyzer for phase noise measurement. In the first path, the power is amplified to about -10 dBm and then applied to the PolM. Both the power and the phase of the microwave signal in this path are finely tuned by the attenuator and the phase shifter to optimize the MIL, thanks to which, the mode hopping in the fiber laser and the OEO are suppressed significantly. To evaluate the stability improvement of the generated microwave signal, the electrical spectrum with a span of 5 MHz of the beat note at the output of the PD is again measured and recorded by the ESA for 20 min with a time interval of 60 s, as shown in Fig. 7(b). As can be clearly seen all the undesired modes are suppressed, and there is no obvious frequency hopping and shifting over 20 min. The stability of the mode-hopping-free beat note in Fig. 7(b) indicates that: 1) the MIL enables that the DW-SLM fiber laser operates at ω_{1x} and ω_{2y} without mode hopping and shifting; 2) the MIL ensures that the OEO works also in the single frequency mode without frequency hopping and power fluctuation. Thus, significantly enhancement of the long-term stability of the generated microwave signal is verified.

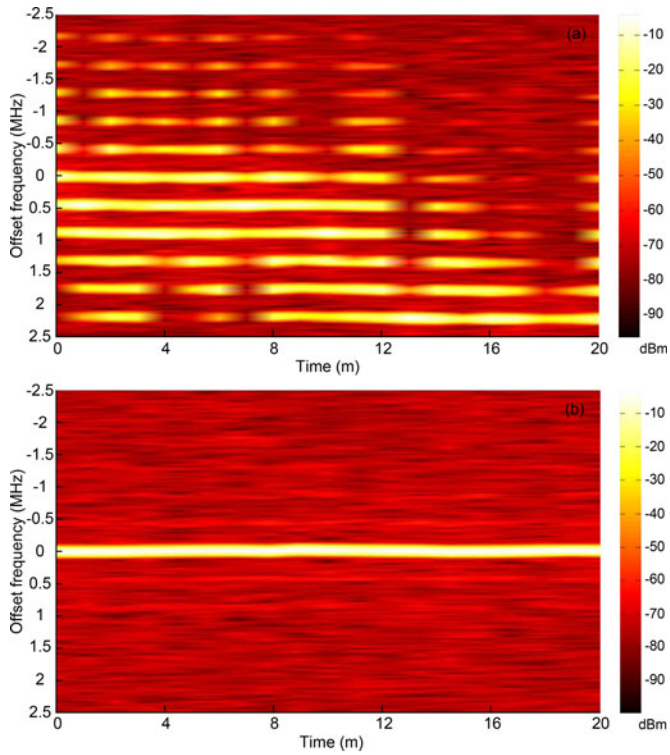

Fig. 7. The comparison of the generated microwave signal without and with the MIL. (span: 5 MHz; RBW: 4.7 kHz).

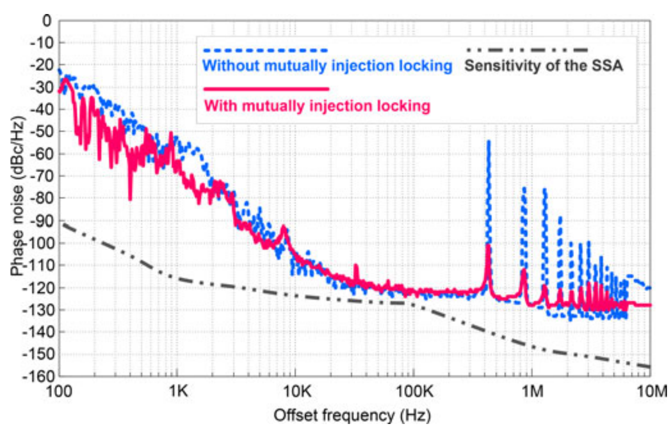

Fig. 8. Measured phase noise of the generated 11.8 GHz signal without (dashed line) and with (solid line) the MIL.

In the second path, the microwave signal is amplified to about −5 dBm and then sent to an Agilent E5052B signal source analyzer incorporating an Agilent E5053A downconverter where the phase noise of the generated microwave signal with and without MIL is measured, as shown in Fig. 8. When the OEO is disconnected at the output port of the PD, no MIL is enabled. The generated microwave signal experiences severe mode hopping and shows large spurs at 320 kHz and its harmonics in the phase noise curve. When the OEO is closed, not only the phase noise measurement becomes stable and the phase noise below 1-kHz offset frequency is improved by about 10 dB, but also the spurs are substantially reduced by as large as almost 60 dB. A phase noise of −105 dBc/Hz at 10-kHz offset frequency is obtained.

IV. Conclusion

A novel approach to generating a stable microwave signal without frequency-hopping and power fluctuation based on the MIL of an OEO and a DW-SLM fiber laser was proposed and experimentally demonstrated. Thanks to this MIL between the DW-SLM fiber laser and the OEO, the operation stability of the system was significantly enhanced. The long-term stability of the generated microwave signal at 11.8 GHz with a phase noise of −105 dBc/Hz at 10-kHz offset frequency was demonstrated. During 20 min observation, no frequency hopping and shifting was recorded.

References

[1] X. S. Yao and L. Maleki "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

[2] G. Grosskopf, D. Rohde, R. Eggemann, S. Bauer, C. Bornholdt, W. Mohrle, and B. Sartorius, "Optical millimeter-wave generation and wireless data transmission using a dual-mode laser," *IEEE Photon. Technol. Lett.*, vol. 12, no. 12, pp. 1692–1694, Dec. 2000.

[3] J. P. Yao "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.

[4] A. J. Seeds and K. J. Williams, "Microwave photonics," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4628–4641, Dec. 2006.

[5] M. A. Quintela, R. A. Perez-Herrera, I. Canales, M. Fernández-Vallejo, M. Lopez-Amo, and J. M. López-Higuera, "Stabilization of dual wavelength erbium-doped fiber ring lasers by single-mode operation," *IEEE Photon. Technol. Lett.*, vol. 22, no. 6, pp. 368–370, Mar. 2010.

[6] X. S. Yao and L. Maleki, "Multiloop optoelectronic oscillator," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[7] W. Li and J. P. Yao, "A wideband frequency-tunable optoelectronic oscillator incorporating a tunable microwave-photonic filter based on phase-modulation to intensity-modulation conversion using a phase-shifted fiber Bragg grating," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 6, pp. 1735–1742, Jun. 2012.

[8] D. Eliyahu, L. Wei, E. Dale, A. A. Savchenkov, V. S. Ilchenko, A. B. Matsko, D. Seidel, and L. Maleki, "Resonant widely tunable opto-electronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 25, no. 15, pp. 1535–1538, Aug. 2013.

[9] O. Okusaga, E. J. Adles, E. C. Levy, W. Zhou, G. M. Carter, C. R. Menyuk, and M. Horowitz, "Spurious mode reduction in dual injection-locked optoelectronic oscillators," *Opt. Exp.*, vol. 19, no. 7, pp. 5839–5854, Mar. 2011.

[10] J. L. Zhang, C. Y. Yue, G. W. Schinn, W. R. L. Clements, and J. W. Y. Lit, "Stable single-mode compound-ring erbium-doped fiber laser," *J. Lightw. Technol.*, vol. 14, no. 1, pp. 104–109, Jan. 1996.

[11] S. Rota-Rodrigo, L. Rodriguez-Cobo, M. A. Quintela, J. M. Lopez-Higuera, and M. Lopez-Amo, "Dual-wavelength single-longitudinal mode fiber laser using phase-shift Bragg gratings," *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 5, pp. 1–5, Sep./Oct. 2014.

[12] S. Pan and J. Yao, "A wavelength-switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser for switchable microwave generation," *Opt. Exp.*, vol. 17, no. 7, pp. 5414–5419, Mar. 2009.

[13] Z. Tian, C. Chen, and D. V. Plant, "Single- and dual-wavelength fiber ring laser using fiber microdisk resonator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 22, pp. 1644–1646, Nov. 2010.

[14] X. Chen, Z. Deng, and J. P. Yao, "Photonic generation of microwave signal using a dual-wavelength single-longitudinal-mode fiber ring laser," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 804–809, Feb. 2006.

[15] G. Ducournau, P. Szriftgiser, T. Akalin, A. Beck, D. Bacquet, E. Peytavit, and J. F. Lampin, "Highly coherent terahertz wave generation with a dual-frequency Brillouin fiber laser and a 1.55 μm photomixer," *Opt. Lett.*, vol. 36, no. 11, pp. 2044–2046, Jun. 2011.

[16] J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, "40 GHz electro-optic polarization modulator for fiber optic communications systems," *Proc. SPIE*, vol. 5577, pp. 133–143, 2004.

[17] Y. Painchaud, M. Aubé, G. Brochu, and M. Picard, "Ultra-narrowband notch filtering with highly resonant fiber Bragg gratings," presented at the *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, Karlsruhe, Germany, 2010, Paper BTuC3.

[18] W. Li, M. Li, and J. P. Yao, "A narrow-passband and frequency-tunable micro-wave photonic filter based on phase-modulation to intensity-modulation conversion using a phase-shifted fiber Bragg grating," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 5, pp. 1287–1296, May 2012.

[19] X. M. Liu and C. Lu, "Self-stabilizing effect of four-wave mixing and its applications on multiwavelength erbium-doped fiber lasers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2541–2543, Dec. 2005.

[20] M. Nakazawa, E. Yoshida, E. Yamada, and Y. Kimura, "A repetition rate stabilized and tunable, regeneratively mode-locked fiber laser using an offset-locking technique," *Jpn. J. Appl. Phys.*, vol. 35, pt. 2, no. 6, pp. L691–L694, Jun. 1996.

[21] K. Koizumi, M. Yoshida, T. Hirooka, and M. Nakazawa, "10 GHz, 1.1 ps optical pulse generation from a regeneratively mode-locked Yb fiber laser in the 1.1 m band," *Opt. Exp.*, vol. 19, no. 25, pp. 25426–25432, Dec. 2011.

[22] X. S. Yao, L. Davis, and L. Maleki, "Coupled optoelectronic oscillators for generating both RF signal and optical pulses," *J. Lightw. Technol.*, vol. 18, no. 1, pp. 73–78, Jan. 2000.

[23] F. Quinlan, C. Williams, S. Ozharar, S. Gee, and P. J. Delfyett, "Self-Stabilization of the optical frequencies and the pulse repetition rate in a coupled optoelectronic oscillator," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2571–2577, Aug. 2008.

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