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Frequency-tunable Optoelectronic Oscillator With Synchronized Dual-Wavelength Narrow-Linewidth Laser Output

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ABSTRACT Synchronized dual-wavelength narrow-linewidth lasers and a wideband frequency-tunable optoelectronic oscillator are simultaneously realized using mutual-injection-locked distributed feedback (DFB) lasers. The two laser modes serve as the seeding light and a microwave photonic filter for the optoelectronic oscillation. Mutual-injection locking between the two DFB lasers through a delay fiber loop results in synchronized narrow-linewidth operation. Microwave tuning from 19 to 41 GHz has been obtained through thermal-tuning of the DFB lasers, with the single-sideband phase noises below −100 dBc/Hz at a 10-kHz frequency offset from the carrier. Laser linewidth has been reduced from several-MHz to kHz with a linewidth reduction factor over 10^4.

INDEX TERMS Microwave photonics, microwave generation, semiconductor lasers.

I. INTRODUCTION

High-quality signals, including both microwave and photonic (laser) signals, are highly desirable in their respective application fields. The phase noise and linewidth are two closely related parameters in evaluating the signal quality in terms of spectrum purity. Microwaves are usually evaluated by the phase noise, while laser signals are usually evaluated by the linewidth. Commercially available high-performance microwave source can reach a phase noise level in the range of −120 to −100 dBc/Hz at a 10-kHz offset from the carrier frequency of 10 to 40 GHz. Commercial semiconductor lasers for optical communication normally have linewidths around several-MHz. Narrow-linewidth semiconductor lasers can reach linewidth below 10 kHz. Traditionally, microwave phase noise and laser linewidth are two parameters that need to be independently optimized due to the difference in working principle and structure of the microwave and photonic devices. With the emerging development of microwave photonics, radio over fiber (RoF) and high precision metrology technologies, there are increasing demands on the adoption of both low-phase-noise microwave source and narrow-linewidth lasers. One typical example is the optical comb generation with narrow-linewidth [1], [2], which can be used for coherent-detection links. In most cases, this will result in two sets of expensive equipment or devices, i.e. high-quality microwave sources, and narrow-linewidth lasers. It would be attractive if both high-quality microwave signal and narrow-linewidth laser can be simultaneously obtained by only using ordinary microwave components and semiconductor lasers. However, there is a lack of relevant reports on such structures.

To obtain a high-quality microwave signal, optoelectronic oscillator (OEO) structures are usually adopted due to its superior performance in phase noise, especially at high frequency [3]–[5]. The oscillation frequency of an OEO is determined by the center frequency of the narrowband bandpass filter (BPF), which is usually realized through electrical BPF. However, the bandwidth and tunability of the electrical BPFs are limiting factors to high-performance tunable OEOs. In recent years, various types of microwave photonic filters (MPFs) have been embedded into the oscillation loop to overcome the limitation of the electrical BPF. Typical MPF schemes include phase-to-intensity modulation (PM-IM) by using a phase-shifted fiber Bragg grating (PS-FBG) [6], a tunable optical bandpass filter [7], [8] or the stimulated Brillouin scattering effect [9], [10] to change the phase or amplitude of the phase modulated sidebands. A dual-mode amplified feedback laser [11], [12], a Fabry-Perot laser diode [13] or a DFB laser under external optical injection or delayed self-feedback [14]–[17] can also be used as MPFs.

By using OEOs as the driving source, highly coherent optical carriers can be obtained. However, by inspecting the individual linewidth of the optical line components, they are normally in the range of MHz or even worse. To realize narrow-linewidth operation, dedicated narrow-linewidth lasers are usually required [2]. Alternatively, a delayed self-injection scheme can be used to reduce the laser linewidth [18].

In this paper, we propose and demonstrate the simultaneous realization of dual-wavelength narrow-linewidth lasers and a frequency-tunable OEO based on optically mutual-injection-locked thermally-tuned distributed feedback (DFB) lasers with optoelectronic feedback. Only two thermally-tuned DFB lasers, a single RF amplifier, a photodetector and two coils of optical fiber are required in the proposed scheme. By tuning the heating power, tunable microwave signal can be obtained ranging from 19 GHz to 41 GHz with single-sideband (SSB) phase noise below −100 dBc/Hz at a 10-kHz frequency offset from the carrier. Two synchronized lasers with linewidth on the level of kHz are obtained due to delayed self-injection. The proposed structure can be used as the coherent carrier generators for RoF links or injection source for comb generators.

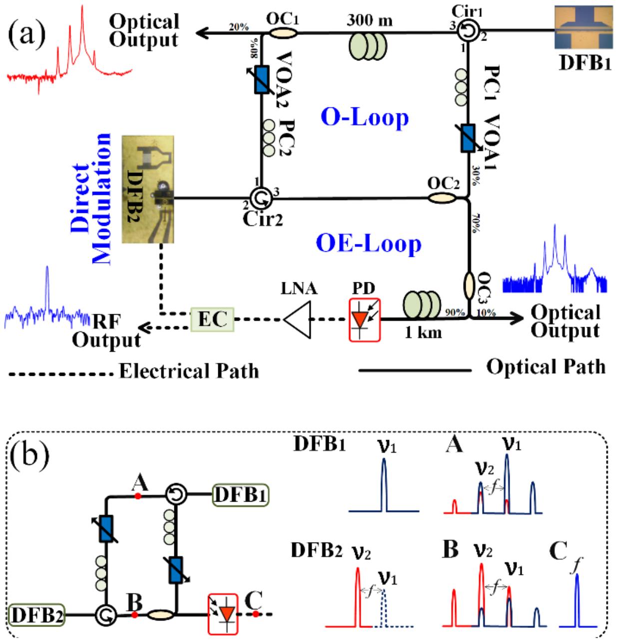

FIGURE 1. **(a) Schematic of the experimental setup. Cir, Circulator; VOA, Variable optical attenuator; PC, Polarization controller; PD, Photodetector; LNA, Low noise amplifier; EC, Electrical coupler; OSA, Optical spectrum analyzer. (b) Illustration operation principle of the two mutual-injection-locked DFB lasers.**

II. PRINCIPLE AND EXPERIMENT SETUP

The schematic diagram of the proposed OEO is illustrated in Fig. 1 (a). It is based on the mutual-injection locking of two thermally-tuned DFB lasers (DFB$_1$ and DFB$_2$) with the assistance of an optoelectronic oscillation loop (OE-Loop). The oscillation frequency of the OE-Loop is determined by the frequency difference between the two DFBs, the beating signal of which forms an equivalent MPF. The center frequency of the OEO can be tuned by changing the wavelength of the DFBs through thermal tuning. DFB$_2$ is directly modulated by the amplified RF signal converted from the beating signal via a photodetector. Due to the photon-photon resonance effect, a high modulation response can be achieved at the detuned frequency. Neither a high-speed external modulator nor an electrical BPF is necessary for this configuration.

The synchronization between the two DFBs is realized through the optical mutual-injection locking between one laser mode and the other laser's sidebands either resulting from the modulation (via the directly modulated DFB$_2$) or the optical carrier regeneration (via DFB$_1$). As shown in Fig. 1(a), the light from DFB$_1$ at a wavelength of λ_1 (frequency ν_1) passes through Cir$_1$ into an optical coupler (OC$_1$). One part (20%) of the light is used for the optical spectrum and the linewidth measurement. The other part (80%) is injected into DFB$_2$ through Cir$_2$ and regenerated as a sideband at ν_1 accompanying the main modes (wavelength λ_2, frequency ν_2) of DFB$_2$. Then, ν_1 and ν_2 pass through Cir$_2$ again and are divided into two part by an OC$_2$ (70:30). One part (70%) of the optical power is detected by a photodetector (Finisar XPDV2120R) to convert the beating signal into an RF signal ($f = \nu_1 - \nu_2$), which is then amplified by an RF low noise amplifier (LNA) with a gain of 40 dB from 20 to 40 GHz. The amplified RF signal is then used to directly modulate DFB$_2$. The other part (30%) of the optical power is injected back into DFB$_1$ and circulates through Cir$_1$ and DFB$_2$ to form the optical mutual-injection loop (O-Loop). In the OEO, the beating signal serves as the seeding signal to initiate the oscillation. The required RF gain is lower than traditional OEOs which start oscillation from noise. Once the modulation starts, one of the modulation sideband of DFB$_2$ will coincide with ν_1 as shown in Fig. 1(b). The modulation sideband will lock DFB$_1$ in the O-Loop, resulting in a synchronized dual-wavelength output.

On the other hand, the two DFBs are actually also injection locked by their delayed replica in the O-Loop. The delayed self-injection will considerably reduce the laser linewidth [19]. Besides, the equivalent bandwidth of the MPF will also be narrowed due to the narrowed beating signals.

Frequency tuning is realized by controlling the wavelength difference between the two DFBs through current-controlled thermal tuning. The Ti thin-film heaters integrated with the two DFBs have an electrical resistance of 1300 Ω which provide a high wavelength tuning efficiency. The detailed fabrication process and performance of the thermally-tuned DFB laser can be found in our previous work [20]. The thermal tuning speed is typically at the level of milliseconds. To further increase the tuning speed, an electrically tuned distributed Bragg reflector laser (DBR) can be used.

A variable optical attenuator (VOA) is used to adjust the injection strength and a polarization controller (PC) is used to match the polarization state between the injection light and the lasers. The output signal is monitored by an electrical spectrum analyzer (ESA) (Agilent PXA N9030A) and an optical spectrum analyzer (OSA) (Advantest Q8384). In the linewidth measurement, a tunable optical filter is used to select a single wavelength. The laser linewidth is measured using a delayed self-heterodyne method with a frequency-shift of 70 MHz, and a delay fiber of 85 km (corresponding to a measuring limit of 750 Hz for Lorentz lineshape).

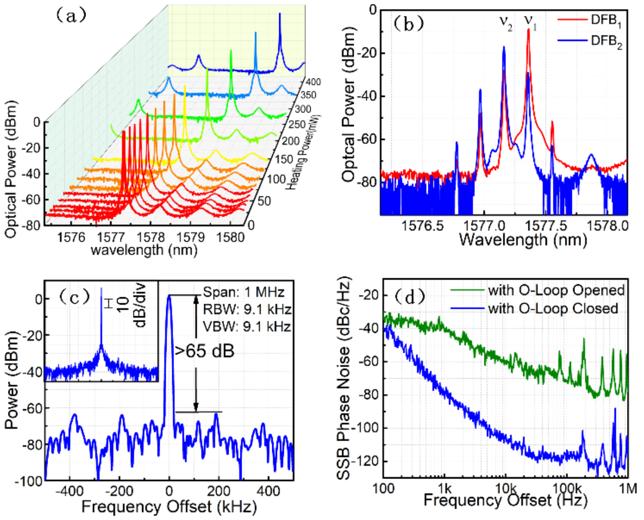

FIGURE 2. (a) Optical spectrums of DFB$_1$ at different heating power, (b) optical spectrum of the two DFB lasers with O-Loop and OE-Loop closed, (c) the generated 23.3-GHz microwave signal under a 1-MHz span. Inset: the RF spectrum in a 1-kHz span with a 1-Hz RBW. (d) Measured SSB phase noise spectrums of the generated signal with O-Loop closed (blue line) and O-Loop opened by disconnecting port 1 of Cir$_1$ (green line).

III. EXPERIMENT RESULTS

In the experiment, DFB$_1$ was mounted on a Cu heat-sink, while DFB$_2$ was mounted on a GSG subcarrier. The emission lights from both DFB lasers were coupled by tapered fibers with anti-reflection coatings. The working temperature was stabilized at 25^{circ} by two thermo-electric coolers (TECs), separately. The thermally-tuned optical spectra of DFB$_1$ (with a fixed bias current of 90 mA) is shown in Fig. 2(a). With the heating power increasing from 0 to 420 mW, the emission wavelength increased from 1577.30 to 1579.41 nm, with a thermal tuning efficiency of 0.005 nm/mW and a tuning range of 2.11 nm. The side-mode suppression ratio of the emission light was above 46 dB during the wavelength tuning. When DFB$_1$ was biased at 90 mA with 9.90-mW heating power and DFB$_2$ was biased at 82 mA without heating, the output power was 6.3 dBm and 5.7 dBm, and the peak wavelengths were 1577.36 nm and 1577.17 nm, respectively, corresponding to a beating frequency of 23.3 GHz. By closing the O-Loop and the OE-Loop with an optical injection power of −2.4 dBm and −4.3 dBm for DFB$_1$ and DFB$_2$ measured at port 1 of each Cir, synchronized narrow-linewidth laser modes and high-quality microwave signal were generated. Fig. 2(b) shows the optical spectra of the two DFB lasers. Fig. 2(c) shows the RF spectrum of the generated 23.3 GHz signal in a 1-MHz span, showing a side-mode suppression ratio over 65 dB. The inset in Fig. 2(c) provides a detail of this signal in a 1-kHz span with a 1-Hz resolution bandwidth (RBW). As shown in the blue line in Fig. 2(d), the SSB phase noise is −107 dBc/Hz at a 10-kHz frequency offset from the carrier when both the O-Loop and the OE-Loop are closed. The maximal phase noise of the generated microwave signal at the spurious modes is −88 dBc/Hz, indicating a good side-mode suppression. For comparison, the phase noise of the microwave signal when the O-Loop is open by disconnecting the Cir$_1$ at port 1 is plotted as the green line in Fig. 2(d). With the O-Loop is open, the synchronization between the two DFB lasers and the delayed self-injection is blocked, the phase noise drastically deteriorates from −107 dBc/Hz to −60 dBc/Hz at a 10-kHz frequency offset from the carrier.

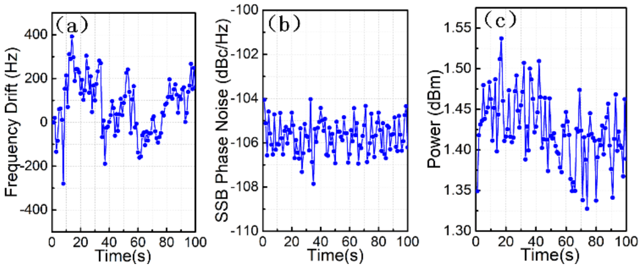

FIGURE 3. Variation of the (a) carrier frequency, (b) phase noise at a 10-kHz carrier frequency offset and (c) carrier power within 100 seconds of continuous measurement.

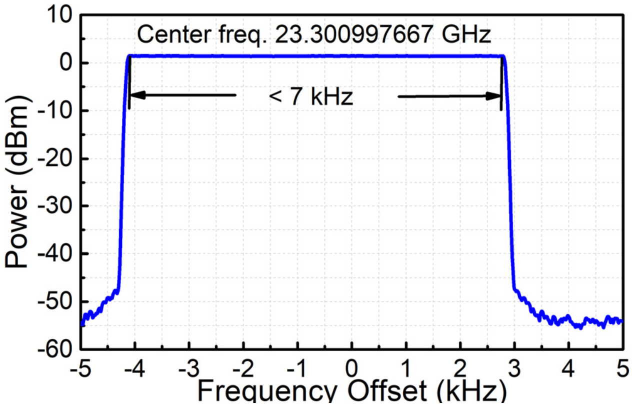

FIGURE 4. Carrier frequency drifts in 20 miniutes.

The carrier frequency, phase noise and carrier power fluctuations of the generated 23.3-GHz signal were measured by using the "spot frequency" mode of the ESA at a sampling rate of 1 sample per second. As shown in Fig. 3, within a 100-second continuous measurement, the carrier frequency drift is < ± 400 Hz, the phase noise variation at a 10-kHz carrier frequency offset is < ± 2 dB and the carrier power variation is < ± 0.125 dB. During a 20-minute of continuous observation in a room environment by using the "Max-Hold" function of the ESA, as the trace shown in Fig. 4,

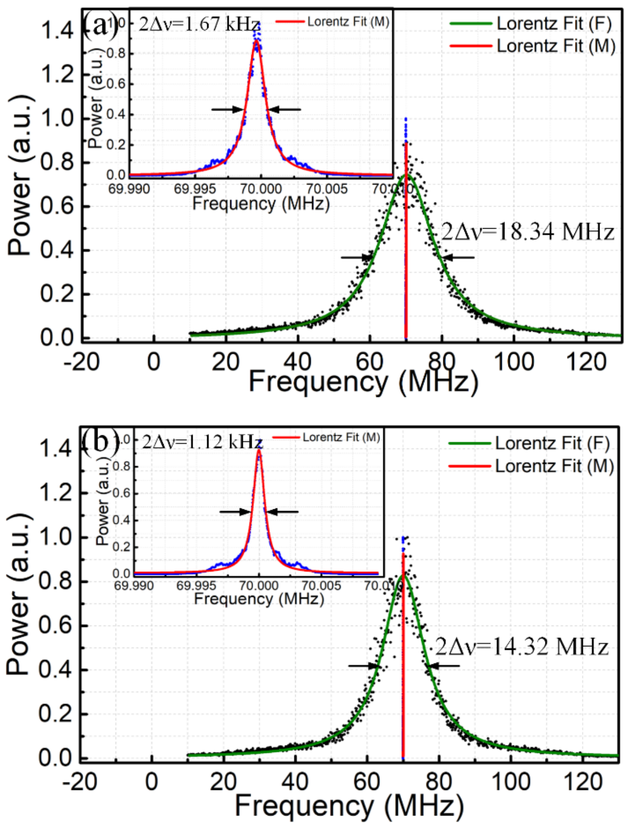

FIGURE 5. (a) Linewidth of DFB$_1$ and (b) DFB$_2$ working in the free-running state and the mutual-injection-locked state. F: Free-running state; M: Mutual-injection-locking state. Inset in (a) and (b) zoom-in view of the linewidth with DFB$_1$ and DFB$_2$ working in the mutual-injection-locking state.

the frequency drift of this signal is less than 7 kHz without mode hopping.

Fig.5 shows the linewidths of the two DFB lasers working in the free-running state and the mutual-injection-locked state with optoelectronic feedback. The linewidth evaluation of the individual wavelength was accomplished with the assistance of an optical tunable filter. As can be seen in Fig. 5, the linewidth of DFB$_1$ is reduced from 9.17 MHz to 0.84 kHz and DFB$_2$ is reduced from 7.16 MHz to 0.56 kHz with a compression factor over 10^4. Even though the measured linewidth has reached the linewidth measurement limit, it is still can be deduced that the linewidth is on the kHz or sub-kHz level.

By tuning the heating power of DFB$_1$ from 0 to 33.94 mW with DFB$_1$ biased at 90 mA, and DFB$_2$ biased at 82 mA without heating, the oscillation frequency can be continuously tuned in a wide range from 18.3 to 43.3 GHz. Fig. 6(a) shows the overlapped RF spectra of the generated microwave signal, which was tuned in a 1-GHz step. The inset in Fig. 5(a) is the 40.3-GHz microwave signal in a 1-kHz span with a 1-Hz RBW. The tuning range is limited by the bandwidth of LNA, and the carrier power of the generated microwave signal is a clearly roll-off of the frequencies below 19 GHz and above 41 GHz due to insufficient gain. Further tuning can be expected if a broadband electrical amplifier is adopted.

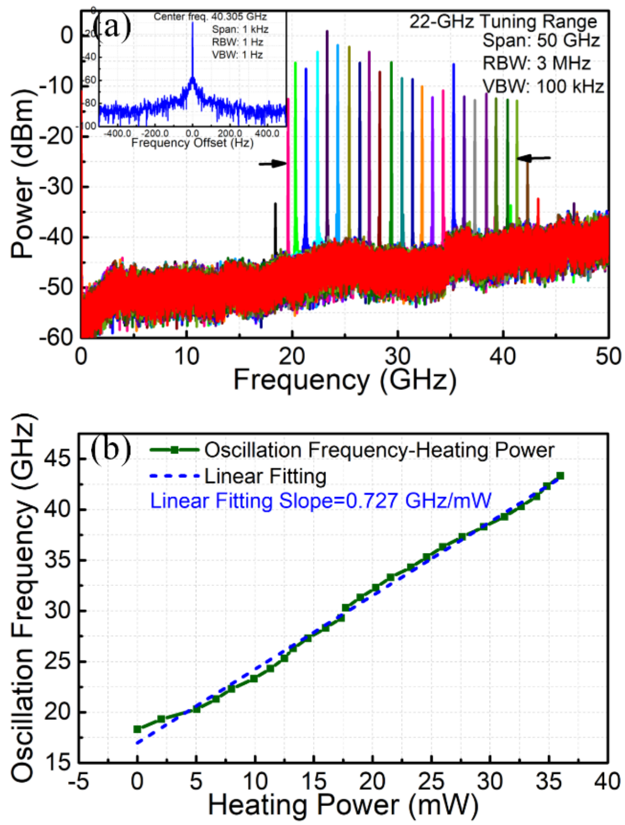

FIGURE 6. (a) Spectra of the generated microwave signal with a frequency tuning range of 19 to 41 GHz with a tuning step of 1 GHz. Inset: the 40.3 GHz microwave signal in a 1-kHz span with a 1-Hz RBW. (b) The relationship between the oscillation frequency and heating power (green + symbol) and its linear fitting curve (blue dash).

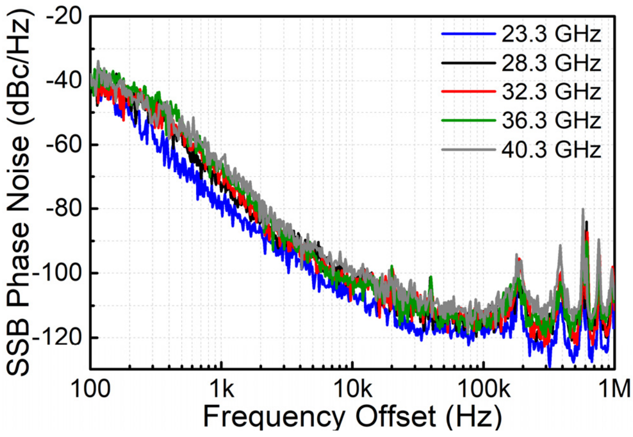

FIGURE 7. Measured SSB phase noise performance of the generated signal at different oscillation frequencies.

As depicted in Fig. 6(b), the oscillation frequency increases almost linearly with the increase of heating power at a linear fitting slope of 0.727 GHz/mW.

Fig. 7 shows the SSB phase noise performance of the generated microwave signal at different oscillation frequencies. The lowest SSB phase noise was measured to be −107 dBc/Hz at a 10 kHz offset from the carrier frequency of 23.3 GHz, while the SSB phase noises at other frequencies were below −100 dBc/Hz, which indicates the advantage of generating a low phase noise microwave signal at a high frequency.

IV. CONCLUSIONS

In summary, we propose and demonstrate a synchronized dual-wavelength narrow-linewidth laser generation and frequency-tunable OEO scheme based on the optically mutual-injection-locked thermally-tuned DFB lasers with optoelectronic feedback. Two synchronized laser modes with linewidth below kHz were realized. The beating signal also functions as a narrow-passband microwave photonic filter to determine the oscillation frequency. By tuning the heating power of the thermally-tuned DFB laser, frequency-tunable microwave signals ranging from 19 GHz to 41 GHz with SSB phase noise below −100 dBc/Hz were obtained. Broader frequency tuning range can be expected by using a broadband RF amplifier.

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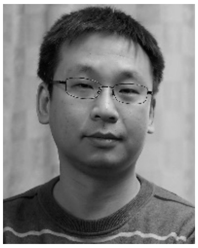

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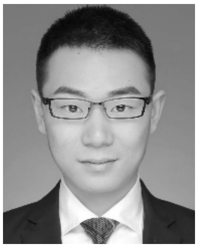

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