Self-injection locking dual-DFB lasers based on a micro-resonator for ultra-low noise microwave generation

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ABSTRACT

A novel scheme for generating ultra-narrow linewidth and ultra-low noise photonic microwave based on simultaneous self-injection locking of dual DFB lasers is proposed and demonstrated. Herein, two narrow linewidth DFB lasers can be independently achieved by Rayleigh backscattering excited in a micro-resonator as feedback for self-injection locking. The 3-dB linewidth of the DFB laser is compressed from 320 kHz to 1.5 kHz, which is narrowed by 2 orders of magnitude. Based on dual narrow linewidth lasers locked to the same micro-resonator, an all-optical high-performance photonic microwave signal is generated by using the optical heterodyne method. The photonic microwave signal with the single sideband phase noise of −102 dBc/Hz and frequency noise of 600 Hz^2/Hz is obtained at a frequency offset of 1 MHz for the generated 5.42 GHz microwave. The proposed scheme is also applicable to any other type of lasers such as VCSEL, fiber lasers et al, which provides a new perspective for the generation of ultra-low noise microwave signals.

Keywords: Self-injection locking, micro-resonator, microwave generation, ultra-low noise

1. INTRODUCTION

Ultra-low noise microwave sources with unique advantages such as low transmission loss and immunity from electromagnetic interference have been widely used in many industrial and military applications, such as wireless communication, phased-array radar, remote distributed antenna, and hybrid lidar/radar1-4. Many methods have been proposed to generate photonic microwave signals, including optical heterodyne detection, optical modulation, external light injection locking, laser mode-locking, optical frequency comb and photoelectric oscillation, etc5-10. Among them, optical heterodyne detection is one of the most promising ways to generate microwave signal. Two optical signals with different frequencies are used for heterodyning, which can be dual frequency laser or two independent lasers. For dual frequency lasers which are achieved by two resonance modes in a single laser cavity, the noise generated in the cavity has an equivalent impact on the two laser modes, which can be eliminated in the heterodyne process to improve the quality of the microwave signal. However, the strong gain competition between the two lasing modes makes it difficult to achieve separate control of the output power and wavelength, which has limitation to tolerate the power fluctuations and tune the frequency of the microwave signals. Two independent lasers have high flexibility in tuning the wavelength and power of each laser to realize reconfigurable microwave signals. However, the phase noise and linewidth of the two lasers will affect the noise and stability of the due to the free running of two independent lasers11. Self-injection locking is a perfect method to lock dual independent lasers to maintain the stability and low noise of the laser12. Distributed feedback (DFB) lasers at the telecom wavelength are good candidates for microwave signals as they have compact size and low cost. Although a variety of self-injection locking schemes have been applied to DFB lasers to generate microwave signals, it still remains challenging to obtain a compact all-optical and low noise photonic microwave. In this paper, we propose and demonstrate a novel scheme, where two independent single-frequency semiconductor DFB lasers are simultaneously self-injection locked into a high-Q on-chip micro-resonator for generating ultra-low noise microwave signals. The single sideband phase noise of −102 dBc/Hz is obtained at a frequency offset of 1 MHz for the generated 5.42 GHz microwave signal without any control and feedback system. The instantaneous linewidth of the microwave signal is compressed from 320 kHz to 600 Hz, which is nearly ~600 times compressed. The proposed scheme provides an insight for the generation of ultra-low noise microwave signals with two independent DFB lasers, which can be further applied to other kinds of lasers and broaden the applications of microwave photonics.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1, where the Rayleigh backscattering excited in a micro-resonator is used as feedback and injected to two independent DFB lasers for self-injection locking to realize narrow linewidth laser signal. Besides, the compressed two DFB lasers will beat with each other to generate ultra-low noise microwave signal. Two DFB lasers are connected with a 3 dB coupler (OC_1) and both outputs are injected into an on-chip micro-resonator with a add-drop configuration. After passing through the micro-resonator, part of the output light is coupled back to the through port connecting with an optical spectrum analyzer (OSA, AQ6370D, YOKOGAWA). Besides, the laser is output through the drop port and connected to 3 dB OC_2 to achieve beat frequency with the 100 Hz linewidth NKT laser. The polarization controller (PC) is used to adjust the polarization state of the NKT laser. An optical isolator (ISO) is used to avoid the backscattering light that will affect the NKT laser and micro-resonator. A photodetector (PD) and an electrical spectrum analyzer (ESA, N9020B, KEYSIGHT) are employed to detect and acquire the microwave signal, respectively.

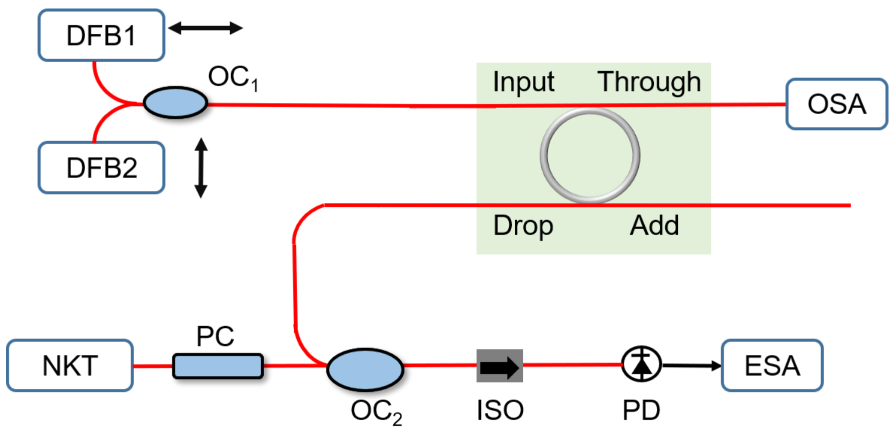

Figure 1. Experimental setup for photonic microwave generation. DFB: Distributed feedback laser; OC: Optical coupler; OSA: Optical spectrum analyzer; PC: Polarization controller; ISO: Isolator; PD: Photodetector; ESA: Electrical spectrum analyzer.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A tunable laser is used to measure the resonance wavelength of the micro-resonator as shown in Fig. 2(a), where two resonance wavelengths corresponding to two vertical polarization modes (TE mode and TM mode) are located at 1549.89 nm and 1549.93 nm. The spectra of one DFB laser are shown in Fig. 2 (b), where the black curve represents the DFB laser in free running state without external cavity feedback, and the blue curve represents the DFB laser with micro-resonator as the injection locking but not at the resonance state. It is obvious that the Rayleigh backscattering excited in a micro-resonator can compress the linewidth of the DFB laser from 6.4 MHz@20dB to 119 kHz@20dB. By further adjusting the temperature and current of the DFB laser, we can further tune the wavelength and adjust it to the resonance wavelength of the micro-resonator. The spectra of one DFB laser are shown in Fig. 2 (c), where enhanced backscattering can further narrow the linewidth to 30 kHz@20dB. This indicates that the intensity of the Rayleigh backscattering will influence the linewidth of the self-injection DFB laser. To optimize the linewidth, we can engineer the wavelength to the resonance of the micro-resonator to achieve efficient compression.

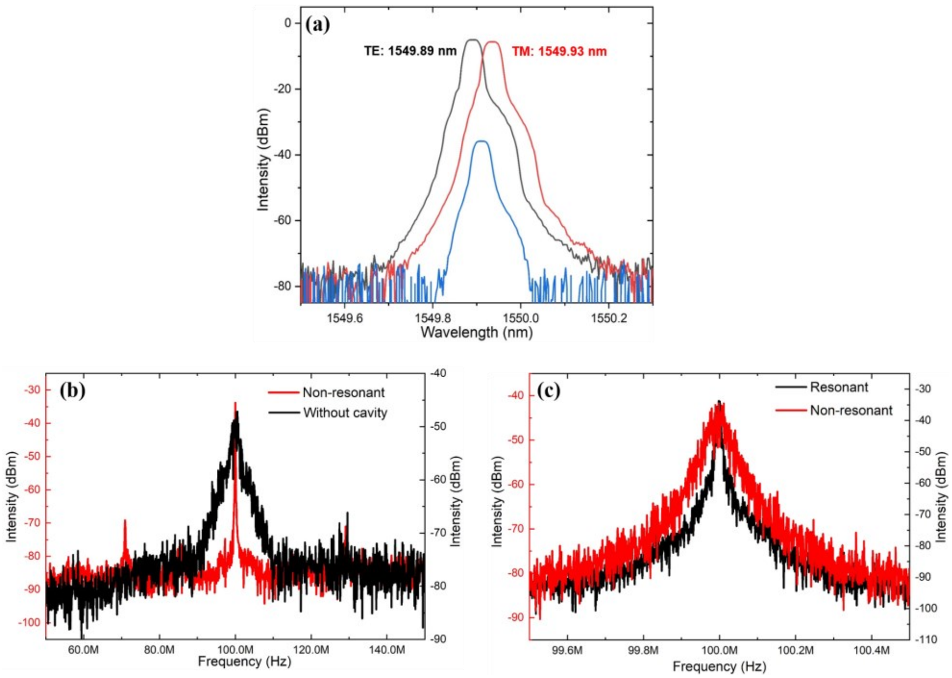

Figure 2. (a) The spectra of adjacent vertical polarization modes in the micro-resonator. (b) and (c) RF spectra of a DFB laser with no feedback, non-resonant feedback, and resonant feedback.

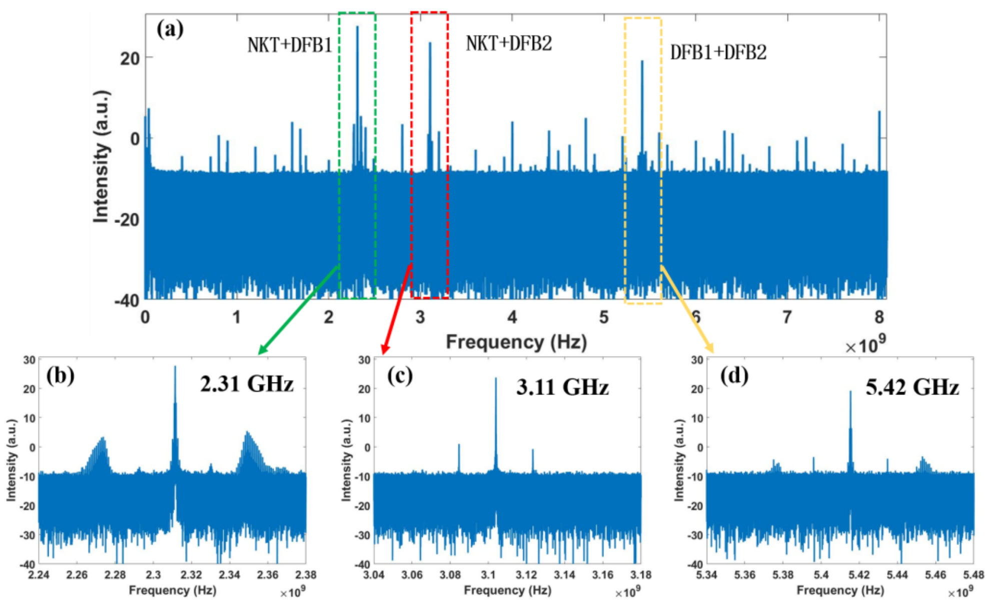

Figure 3. (a) Beat frequency spectra of the output signal. RF spectra between (b) NKT+DFB1, (c)NKT+DFB2 and (d) DFB1+DFB2.

To explore the simultaneous compression effect of the micro-resonator on two DFB lasers and the quality of the microwave signals generated, the beat frequency signals between different lasers are detected as shown in Fig. 3(a). As shown in Figs. 3(b) and (c), where DFB1 has a larger linewidth than DFB2. Besides, some stray components are observed in the frequency offset of about 40 MHz, which are mainly introduced by the laser itself and can be optimized by screening lasers. Figure 3(d) shows the beat signal between the two DFBs with a signal frequency of about 5.42 GHz.

At the same time, the linewidth of the signal is wider than that of a single DFB, indicating that the frequency drift of the two DFB lasers is not completely synchronized. It is necessary to control the resonant wavelengths of the micro-resonator to ensure self-injection of two lasers, which can achieve synchronization of two DFB lasers and then generate low noise microwave signal.

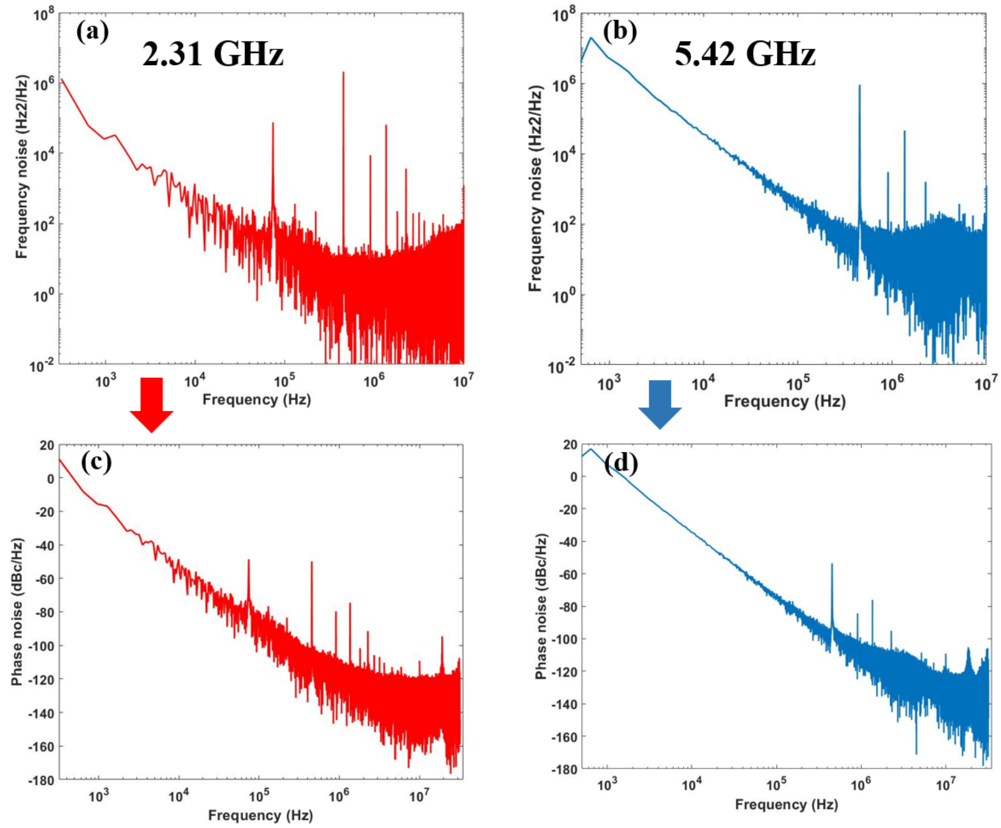

Figure 4. Phase noise of (a) 2.31GHz and (b) 5.42GHz beat frequency signals. (c), (d) Corresponding frequency noise.

To further demonstrate the phase noise characteristics of the compressed laser signal and the generated microwave signal, we measure the single sideband (SSB) phase noise spectra of the laser and microwave signals. The phase and frequency noise of different beat signals is obtained by fast Fourier transform (FFT), as shown in Fig. 4. The phase noise is -110 dBc@1MHz and -102 dBc@1MHz, as shown in Figs. 4(a) and (b), respectively. The corresponding frequency noise is 200 Hz^2/Hz@1MHz and 600 Hz^2/Hz@1MHz respectively, as shown in Figs. 4(c) and (d). The above results shows that the linewidth of two DFB lasers after beating is wider than that of a single laser, which indicates that no phase locking exists between two DFB lasers.

4. CONCLUSION

In this work, we have demonstrated that an ultra-low noise microwave signal can be generated by simultaneous self-injection locking of two DFB lasers through a micro-resonator. The SSB phase noise of −102 dBc/Hz is obtained at a frequency offset of 1 MHz for the generated 5.42 GHz microwave signal under the normal condition. Moreover, the instantaneous linewidth of the microwave signal is compressed from 320 kHz to 600 Hz, which is nearly ~600 times compressed. The on chip micro-resonator with compact structure and high Q factor can be used as the feedback for injection locking of two independent lasers, which can be further explored to injection locking of multiple lasers and microwave signal generation system.

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