Gain-Switched Optical Frequency Comb Source Using a Hybrid Integrated Self-Injection Locking DFB Laser

Shuai Shao, Jiachen Li, Hongwei Chen, *Senior Member, IEEE*, Sigang Yang, and Minghua Chen

***Abstract*—A hybrid integrated gain-switched (GS) optical frequency comb (OFC) source with eight pure continuous comb lines within 3-dB of the spectral envelope peak and a narrow linewidth of 615 kHz is proposed and demonstrated by coupling a silicon nitride microring reflector (MRR) to a commercially available distributed feedback (DFB) laser. Due to the self-injection locking effect induced by the MRR, the carrier-to-noise ratio (CNR) and phase correlation between comb lines are greatly enhanced. In addition, benefiting from the unique merit of gain switching, the resultant comb can also achieve a large frequency spacing adjustment range from 5.55 GHz to 8.7 GHz. This work explores a cost-efficient and robust OFC source for numerous applications, such as radio over fiber (RoF) and coherent optical communication.**

***Index Terms*—Gain switching, integrated optics, optical frequency comb, self-injection locking.**

I. Introduction

An OPTICAL frequency comb (OFC), consisting of a multitude of repeating and equidistant spectral lines, has attracted a great deal of interest in countless fields, such as spectroscopy [1], metrology [2], optical atomic clocks [3], optical communication [4], photonic radar [5], and microwave generation [6]. Among them, OFCs with good spectral flatness, narrow linewidth, and high coherence are especially desired in light detection and ranging (LIDAR) [7], flexible superchannel transmission systems, radio over fiber (RoF) [8], and coherent wavelength division multiplexing (CoWDM) [9]. There are several methods to generate OFCs with the above mentioned characteristics, including use of mode-locked lasers (MLLs) [10], Kerr-comb generation (KCG) via nonlinear microresonators [11]–[14], use of external electro-optic modulators [15], and gain switching [9], [16]–[18]. In particular, gain switching has attracted increasing attention in recent years due to its unique merits of cost efficiency, free spectral range (FSR) tunability, low energy consumption, simple construction, and small footprint. It can be realized by simultaneously applying a direct current (DC) bias signal and a sinusoidal radio frequency (RF) signal to a semiconductor laser. The laser operates in a periodic switch-off state, which can periodically produce short pulses. In the optical spectrum, there are equally spaced spectral lines.

External optical injection has been proven to be an effective method to improve the quality of gain-switched (GS) OFC lines. The master laser provides excitation of a lasing mode to well above the level of the spontaneous emission from the slave laser [9], enabling each pulse to be built up from the external injection light with the same phase rather than from the random spontaneous emission. The generated OFC has a prominent role to play in contributing to the flatness, phase noise, time jitter, and relative intensity noise (RIN) [18], as it follows the characteristics of the master laser [19]. However, in such master-slave configurations, the use of discrete devices such as circulators and polarization controllers undoubtedly entails a large footprint. The system also requires great attention to avoid instability due to various external factors. Although some recent studies have been performed on monolithic integration [18], [20], [21], multiple active devices still result in increased costs. To further improve the quality of OFC lines, self-injection locking is arranged by injecting part of the light output back into the laser through a passive external cavity. Through self-injection locking, lasers can achieve better noise suppression performance, modulation bandwidth enhancement [22], and system stabilization [23]. Research on GS lasers with self-injection locking dates back to the 1990s [24]–[28]. In recent years, with the rapid development of photonic integration technologies, miniaturized GS OFC sources have begun to attract attention [29], [30].

In this paper, a hybrid integrated OFC source based on gain switching with self-injection locking is proposed and demonstrated by butt coupling a commercially available distributed feedback (DFB) laser with a high-Q microring reflector (MRR). The MRR selects only one individual comb line and injects it back into the DFB laser to make each pulse of the laser be built up with the same phase, improving the spectral flatness and coherence of the generated OFC. In addition, the strong self-injection locking effect also reduces the comb line linewidth and phase noise. The MRR is fabricated on a low-loss silicon nitride (Si_3N_4) waveguide platform, and the packaged hybrid OFC source is experimentally characterized. The results show

Manuscript received November 7, 2021; revised December 30, 2021; accepted January 5, 2022. Date of publication January 7, 2022; date of current version February 9, 2022. This work was supported in part by the National Key Research and Development Program of China under Grant 2021YFB2800802, and in part by the National Natural Science Foundation of China under Grant 61771285.
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Digital Object Identifier 10.1109/JPHOT.2022.3141424

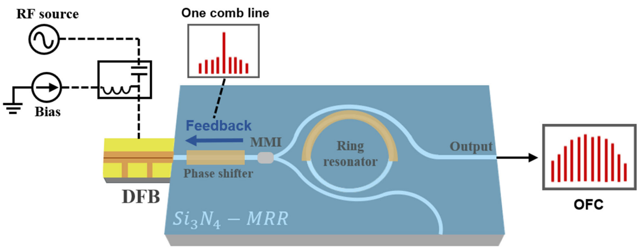

Fig. 1. Schematic diagram of the proposed hybrid OFC source, composed of a commercially available DFB laser and a butt-coupled high-Q Si_3N_4-based MRR. The MRR selects only one individual comb line and reflects it back, achieving self-injection locking of the DFB laser.

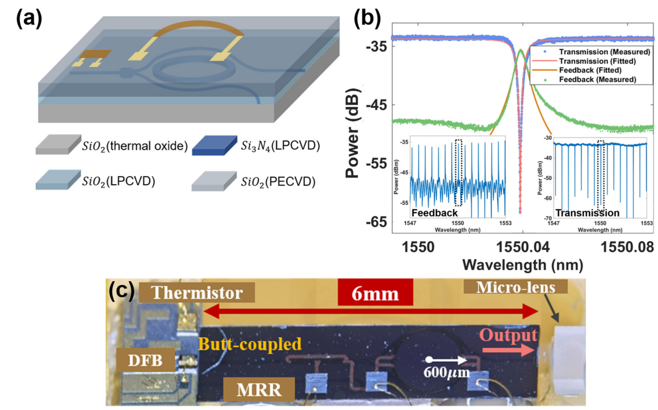

Fig. 2. (a) Waveguide structure of the MRR chip. (b) Transmission spectrum and feedback spectrum of the MRR; the FSR is 50 GHz, and the FWHM is 562 MHz. The Q of the MRR is calculated to be 3.45×10^5. (c) Microscope image of the hybrid OFC source. The MRR chip is 6 mm–1.5 mm in size. The DFB laser and MRR chip are butt coupled and a lens group is placed behind the MRR to collect the output light.

the enhancement of flatness from 5 to 8 comb lines within 3-dB of the spectral envelope peak and increment of the carrier-to-noise ratio (CNR) from 27 dB to approximately 40 dB at an FSR of 6.5 GHz. The 3-dB optical linewidth of the comb line is reduced to 615 kHz, narrower than the 7.34 MHz linewidth of the continuous wave (CW) solitary laser. The 50 Hz RF beat tone linewidth also indicates the outstanding OFC phase correlation. Furthermore, the hybrid OFC source can achieve continuously adjustable FSR from 5.55 GHz to 8.7 GHz, exhibiting a larger attainable range than the solitary laser.

II. Principle

The proposed hybrid OFC source is shown in Fig. 1, composed of a commercially available DFB semiconductor laser and an MRR. The MRR consists of one phase shifter, one 50:50 multimode interferometer (MMI), and one ring resonator. The phase shifter can adjust the phase delay of the optical field and the MMI is insensitive to manufacturing tolerances [31], [32]. The input port and feedback port of the ring resonator are connected to the phase shifter through the MMI, which makes the MRR suitable for self-injection locking. The output port and add port of the ring resonator are the same; the former is used for OFC output, and the latter is left connected. An RF sinusoidal signal superimposed with a DC bias signal is directly applied to the DFB laser. The laser is in the GS state and produces optical pulse trains in the time domain and an OFC in the frequency domain. The MRR can be viewed as a reflector whose reflectivity is wavelength dependent. It selects only one comb line from the input OFC and reflects it back, achieving self-injection locking of the DFB laser, while the other comb lines are passed through the MRR without interference. This ensures the output power and avoids the instability caused by mode competition or multiple excitations after multimode injection. The reflection comb line is selected as the carrier line (with a CW frequency) of the DFB laser rather than the other generated sidebands, which has also been proven to be the optimal regime [29]. When the DFB laser realizes self-injection locking, each pulse is derived from the light injected back by the MRR rather than random spontaneous emission, ensuring coherence between pulses and generating a clearer and distinguishable OFC. In addition, the use of a high-Q external cavity can greatly suppress the noise and chirp and extremely extend the laser photon lifetime, leading to a reduction in the comb line linewidth.

III. Design and Fabrication

To achieve the optimal self-injection locking state, the FSR and full width at half maximum (FWHM) of the MRR are designed as 50 GHz and 500 MHz, respectively. The FSR is larger than half the DFB laser gain range, and the FWHM is far less than the RF modulation frequency. These values can ensure that the MRR has only one reflection peak within the OFC spectrum range and reflects only one individual comb line back to the DFB laser, respectively. As a proof of concept, the MRR is fabricated on a low-loss Si_3N_4 waveguide platform [33]. Compared with silicon-on-insulator (SOI), this platform has three main advantages: lower waveguide propagation loss, higher mode matching degree, and broader transparency [22]. The MRR chip structure is shown in Fig. 2(a) and consists of a 0.1 μm-thick low-pressure chemical vapor deposition (LPCVD) Si_3N_4 layer buried in a 2 μm-thick LPCVD SiO_2 cladding layer and a 6 μm-thick plasma-enhanced CVD (PECVD) SiO_2 cladding layer, which were fabricated on a 10 μm-thick SiO_2 layer. The TiN thermal electrode patterned on the surface can change the waveguide refractive index through the thermo-optic effect. Due to the thickness limitation, the waveguide has normal dispersion, and the Kerr soliton state cannot be realized [12]. Therefore, the MRR is mainly used as a high-Q reflector to realize self-injection locking, rather than using the nonlinear effect to produce a Kerr comb.

Fig. 2(c) shows a microscopic image of the MRR; the length of the phase shifter is 2.6 mm, and the radius of the ring resonator is 600 μm. Before coupling to the DFB laser, the transmission spectrum and feedback spectrum of the MRR are measured by an advanced optical spectrum analyzer (OSA, APEX, AP2081B, resolution of 0.16 pm) with a built-in tunable laser source. The output and input ports of the OSA are coupled to the MRR through single-mode fibers. When measuring the reflection spectrum, an optical circulator is used to collect the reflected light. As shown in Fig. 2(b), the FSR is 50 GHz. By fitting the measured spectrum to the standard Lorentz linear function, the FWHM is extracted as 562 MHz, and the Q of MRR is calculated to be 3.45×10^5.

The commercial 1.5-μm DFB laser and MRR chip are butt coupled and encapsulated in a 14-PIN butterfly package, as shown in Fig. 2(c). A micro-collimating lens, an optical isolator, and a lensed fiber are sequentially placed behind the output waveguide of the MRR to collect the output light and prevent external reflection. The coupling losses between the DFB laser and MRR chip and between the MRR chip and lensed fiber are estimated to be -1.8 dB and -2.5 dB, respectively. These values can be further improved by optimizing the misalignment and separation between devices [33]. A thermoelectric cooler (TEC) is also packaged under the laser module to keep the temperature stable.

IV. Experiment and Results

A. Experimental Setup

A DC bias current (20 mA) is first applied to the DFB laser (the threshold is 7 mA). By fine adjustment of the TEC temperature (40.83 °C) and phase shifter, the DFB laser can be optimally self-injection locked to one reflection peak of the MRR [34]. The wavelength of the output light is 1550.87 nm, and the output power is -10.63 dBm with a side-mode suppression ratio (SMSR) of 47 dB. Then, another RF sinusoidal signal generated from an RF source (HP83752B) is superimposed through a bias-tee, and all signals are directly applied to the DFB laser through an RF probe (40A-GSG-200-LP). The resulting OFC is measured by the high-resolution OSA. This order can ensure that the comb line with the carrier frequency is reflected back to the DFB laser rather than the other generated sidebands. For comparison, a solitary laser is also tested under the same TEC temperature. The modulation frequency is chosen to be 6.5 GHz because this is the relaxation oscillation frequency of the laser, at which the carriers and photons have the most sensitive response [35]. The RF signal power is set to 15.6 dBm; in this case, the DFB laser is not completely switched off, and the remaining DC signal can keep the laser in the self-injection locking state for cooperation with the incomplete extinction of the stimulated emission between pulses, which is vital for generating a visible spectrum [36], [37].

B. Flatness and CNR

The spectra in Fig. 3(a) and (b) illustrate the OFC generated by the solitary laser and the hybrid OFC source in the self-injection locking state, respectively. The purity of the OFC is significantly enhanced under the condition of self-injection locking. There are eight continuous, clearly resolved comb lines within a 3-dB spectral window for the hybrid OFC source, compared with five for the solitary laser. The CNR also increases from 27 dB to approximately 40 dB, showing excellent noise suppression and linewidth reduction. Unlike some external optical injection

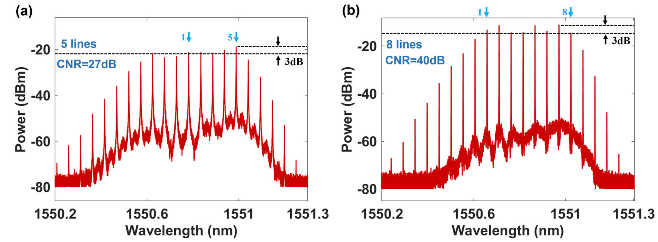

Fig. 3. Resultant OFC obtained by gain switching: (a) solitary laser and (b) hybrid OFC source in the self-injection locking state at an FSR of 6.5 GHz.

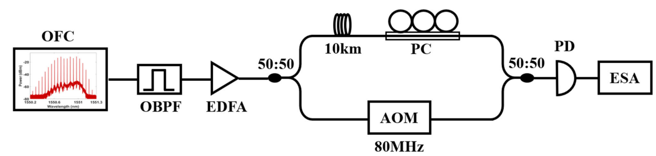

Fig. 4. Experimental schematic of individual comb line linewidth measurement using the delayed self-heterodyne method. OBPF: optical bandpass filter; EDFA: erbium-doped fiber amplifier; PC: polarization controller; AOM: acousto-optic modulator.

configurations, the bandwidth of the total spectrum has no significant increase, which may be due to the relatively weak feedback optical power. In the external injection configurations, the powers of the master and slave lasers can be very close, but for this proposed self-injection feedback structure, the optical power injected back into the laser is approximately 8.9% of the output caused by the 3.6 dB coupling loss and 6.9 dB on-chip insertion loss.

C. Comb Line Linewidth

The linewidth of the individual comb lines is measured by the delayed self-heterodyne (DSH) method [38]. The experimental schematic is shown in Fig. 4. The OFC with an FSR of 6.5 GHz output from the hybrid OFC source is first passed through an optical bandpass filter (OBPF) to select one individual comb line and an erbium-doped fiber amplifier (EDFA) to amplify the signal and then equally divided into two beams through a 50:50 splitter. One beam of light is sent through an acoustic-optic modulator (AOM) to generate a frequency shift of 80 MHz, and the other beam is sent into a 10 km fiber interferometer. The power spectrum of the beat signal from the photodetector (PD) is evaluated by an electrical signal analyzer (ESA, Agilent, N9030 A). As shown in Fig. 5, the 3-dB optical linewidth of the comb line is measured to be 615 kHz, which shows an enormous reduction of over ten times compared with the 7.34 MHz linewidth of the CW solitary laser.

D. Phase Correlation

The phase correlation between comb lines (or pulses in the time domain) is also a key factor for characterizing the OFC quality [39] and is in high demand for numerous applications such as optical frequency synthesizers and low-noise microwave generation. The RF beat tone is measured for this correlation

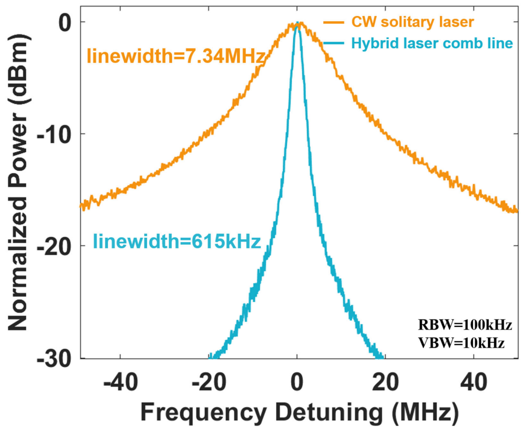

Fig. 5. Power spectrum of the beat signal. The 3-dB optical linewidth of the comb line is 615 kHz, which shows an enormous reduction of over ten times compared with the 7.34 MHz linewidth of the CW solitary laser.

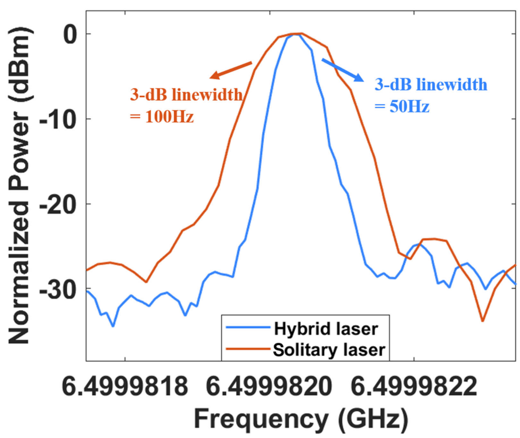

Fig. 6. RF beat tone spectrum of the whole OFCs generated from the hybrid OFC source and the solitary laser. The 3-dB linewidth of the beat tone under self-injection locking is measured to be 50 Hz, indicating outstanding phase correlation.

characterization. If there is a high phase correlation between comb lines, then a pure narrow linewidth RF beat signal appears [40]; otherwise, the signal is broadened with the superposition of the phase noise in each line. The whole OFCs with an FSR of 6.5 GHz generated from the hybrid OFC source and the solitary laser are detected by a high-speed PD and evaluated by an ESA. As shown in Fig. 6, the 3-dB linewidth of the beat tone under self-injection locking is measured to be 50 Hz, narrower than the 100 Hz linewidth of the solitary laser, indicating outstanding phase correlation.

E. FSR Tunability

Benefiting from the unique advantage of gain switching, the hybrid OFC source can generate an OFC with a continuously adjustable FSR, as it is determined by the modulation frequency of the DFB laser. Fig. 7(a) to (d) show the generated OFCs with four different FSRs varying from 5.55 GHz to 8.7 GHz. The bias current remains at 20 mA, and the phase shifter is properly adjusted to ensure that the laser is in the self-injection locking state. Since the gain range of the laser is determined, there are more comb lines within the 3-dB spectral window with decreasing modulation frequency, and the number can reach 10 at the FSR of 5.55 GHz. However, the lower modulation frequency results in more time for the laser to be critically switched-off, during which the spontaneous emission and time jitter between pulses accumulate even in the presence of feedback light [35], resulting in a reduction in the CNR and deterioration of the linewidth. In contrast, the quality of the comb line improves with increasing modulation frequency. Fig. 7(e) to (h) show the OFCs generated by the solitary laser with the same FSRs as those generated by the hybrid OFC source. At an FSR of 5.55 GHz, the comb lines from the solitary laser with a large linewidth and a poor CNR are not suitable for practical application, while the hybrid OFC source can produce ten lines with a CNR larger than 36 dB; under the condition of 8.7 GHz, the solitary laser does not produce continuous comb lines within the 3-dB spectral window, while the hybrid OFC source produces four lines. The comparison shows increment of the maximum and minimum attainable frequency spacing between comb lines by inducing self-injection locking, which can also be proven through the enhancement of the modulation bandwidth [22]. Note that visible spectral lines can still be observed in other frequency spacing ranges but are abandoned due to poor flatness or too few elements.

V. Discussion

The comprehensive improvement of the GS OFC quality (flatness, purity, linewidth, FSR attainable range) with the introduction of self-injection locking has been shown. Compared with the passive mirror as an external cavity shown in [30], the high-Q MRR used in this work has wavelength selectivity. By reasonably designing the FSR (50 GHz) and the FWHM (500 MHz), the MRR reflects only one comb line and injects it back into the laser instead of the whole OFC. This ensures the output power and avoids the instability caused by mode competition or multiple excitations after multimode injection. In particular, the DFB laser and the MRR are butt coupled and hybrid integrated, which makes the OFC source insensitive to environmental disturbances and has the advantages of photon integration, such as high robustness, cost efficiency and compactness. Owing to the use of a higher Q-value whispering-gallery-mode microresonator, [29] exhibits a larger FSR adjustment range and a narrower linewidth. However, the OFCs shown in this work have a higher spectral flatness, which is better for practical applications. In applications such as RoF [8] and multicarrier spectrally efficient transmission [9], the power difference between comb lines should not be too large, as this can cause greater difficulties in signal demodulation between different channels. In addition, the comb line linewidth should be sufficiently narrow to impose higher-order advanced modulation formats. The OFC in this work with high spectral flatness and narrow linewidth can be directly used without additional shaping.

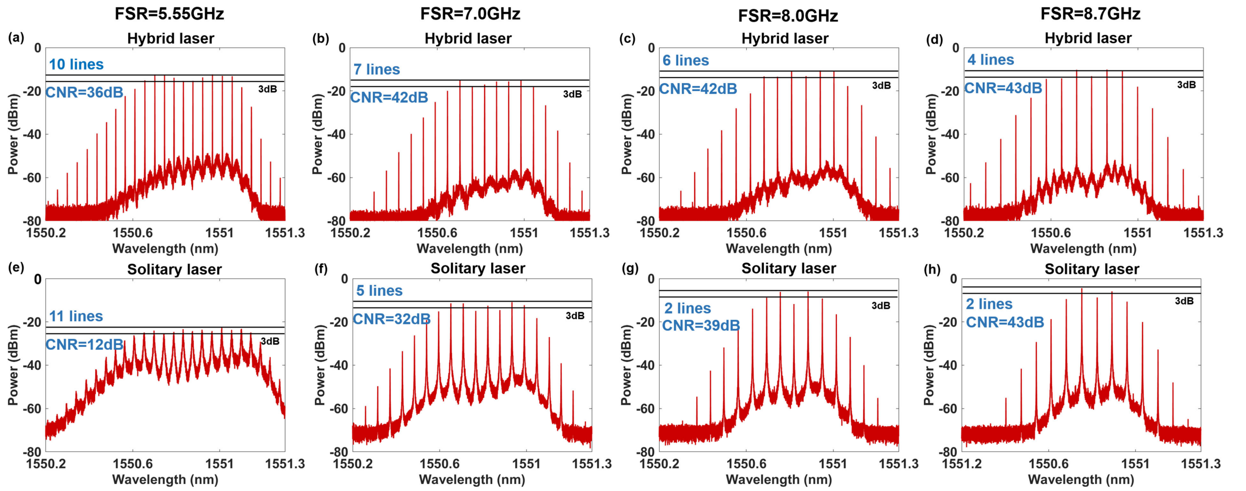

Fig. 7. OFCs with different FSRs generated by the hybrid OFC source: (a) 5.55 GHz FSR with 10 comb lines within the 3-dB window, (b) 7 GHz FSR with 7 lines within the 3-dB window, (c) 8 GHz FSR with 6 lines within the 3-dB window, and (d) 8.7 GHz FSR with 4 lines within the 3-dB window. OFCs with different FSRs generated by the solitary laser: (e) 5.55 GHz FSR with 11 comb lines within the 3-dB window, (f) 7 GHz FSR with 5 lines within the 3-dB window, (g) 8 GHz FSR with 2 lines within the 3-dB window, and (h) 8.7 GHz FSR with 2 lines within the 3-dB window.

VI. Conclusion

In conclusion, a GS OFC source based on a high-Q MRR for self-injection locking is demonstrated and fully characterized. The resultant OFC shows enhanced flatness of eight comb lines within a 3-dB spectral window, a high purity of a 40 dB CNR, a narrow linewidth of 615 kHz, and high phase coherence between comb lines at a 6.5 GHz spacing. The FSR can be continuously adjusted from 5.55 GHz to 8.7 GHz, showing a larger attainable frequency spacing range than the solitary laser. This work makes full use of photonic integration and self-injection locking and has great potential value for various applications.

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