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Low-noise amplification of dissipative Kerr soliton microcomb lines via optical injection locking lasers

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The dissipative Kerr soliton microcomb provides a promising laser source for wavelength-division multiplexing (WDM) communication systems thanks to its compatibility with chip integration. However, the soliton microcomb commonly suffers from a low-power level due to the intrinsically limited energy conversion efficiency from the continuous-wave pump laser to ultra-short solitary pulses. Here, we exploit laser injection locking to amplify and equalize dissipative Kerr soliton comb lines, superior gain factor larger than 30 dB, and optical-signal-to-noise-ratio (OSNR) as high as 60 dB obtained experimentally, providing a potential pathway to constitute a high-power chip-integrated WDM laser source for optical communications.

Keywords: Kerr microcomb; optical injection locking; coherent optical communications.
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1. Introduction

In a wavelength-division multiplexing (WDM) system, optical data signals are transmitted in parallel wavelength channels, significantly enhancing the communication capacity and spectrum efficiency of optic fibers[1]. In today's WDM systems, a multi-wavelength laser source is usually made of a large number of individual lasers, which suffer from random frequency and phase drifts among each other [as shown in Fig. 1(a)]. Therefore, it usually entails heavy optical or electrical processes to compensate the frequency and phase uncertainties among different data channels, thus increasing the overall system complexity[2]. Recently, the invention of a dissipative Kerr soliton (DKS) microcomb generated in a nonlinear optical microcavity offers a new avenue to build high-performance multi-color laser sources for WDM networks[3–5], thanks to its excellent characteristics including high-frequency stability, large comb spacing, wide spectrum, and compatibility with chip integration.

When pumped by a continuous-wave laser, the DKS microcomb can be produced in a high-quality (Q)-factor microcavity relying on a double balance between parametric gain and loss, as well as dispersion and Kerr nonlinearity.

Nowadays, each DKS microcomb can offer hundreds of evenly spaced laser lines with frequency spacing ranging from gigahertz (GHz) to terahertz (THz), while maintaining extremely high mutual coherence among all comb lines[6]. Moreover, the DKS microcomb also has a very smooth spectral envelope across a wide bandwidth that readily covers the full C and L communication band, which is a necessity for WDM systems[7]. Due to these excellent properties, recent demonstration of WDM transmission using DKS microcombs has achieved extremely high aggregate data rates up to 55 $\text{Tbit} \cdot \text{s}^{-1}$, revealing its great potential as the next-generation communication light source[3].

However, the generating dynamics of the DKS microcomb usually suffer from quite low conversion efficiency from the incident pump laser to the generated comb lines[6,8], due to the transient nonlinear interaction and energy transfer between the continuous-wave pump background and the picosecond or femtosecond solitary pulses. This severely constrains the power level of each soliton microcomb line and degrades their applicability to carry high-speed optical data signals. For instances, for a single-soliton microcomb generated in a silicon nitride microring with a Q-factor of 1 million and free-spectrum range (FSR) of 100 GHz, the maximum comb line power is about 30 dB below the incident pump power, equal to an overall energy conversion efficiency $<1\%$ (the power ratio between all comb lines and the pump)[8]. Alternatively, the DKS microcomb generated in a large mode area silica whispering-gallery mode (WGM)

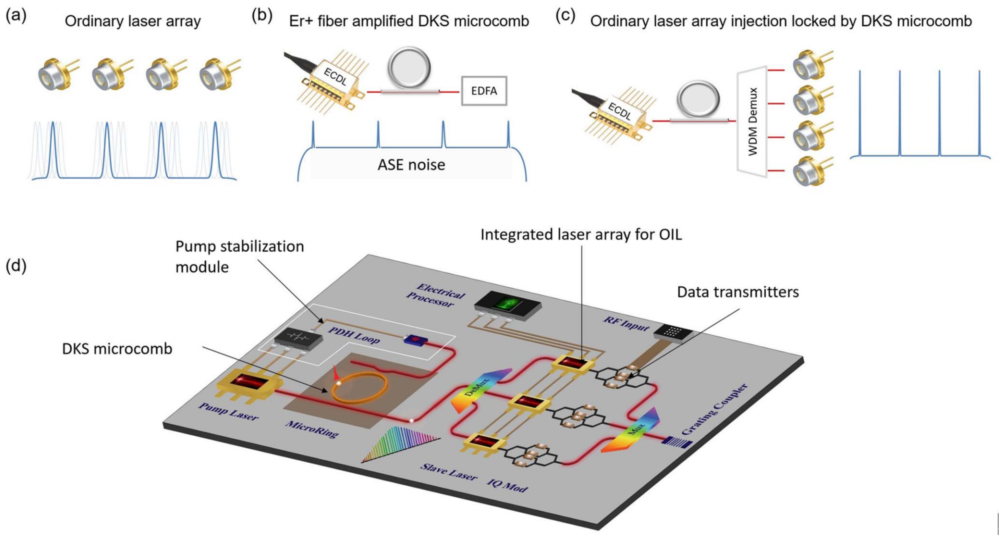

Fig. 1. Principles of OIL-based low-noise amplification of DKS microcomb lines. (a) Conventional multi-wavelength source consists of a large number of discrete lasers showing severe random frequency drift; (b) DKS microcomb generated by an external cavity laser diode (ECDL) amplified by using an EDFA, but at the sacrifice of OSNR degradation; (c) OIL-laser-based DKS microcomb amplification scheme provides simultaneous low noise and high gain. (d) A conceptual image of an integrated chip-scale optical data transmitter using DKS comb lines as WDM data carriers, which are power boosted using the OIL laser scheme.

microcavity can acquire higher power from the pump, thanks to the cavity's lower nonlinear coefficient[9], but the overall energy conversion efficiency is still below 10% (still assuming 100 GHz spacing). Therefore, power amplification is always needed before using the DKS comb lines as carriers to load high bitrate data signals. An erbium-doped fiber amplifier (EDFA) is usually adopted to boost the power of DKS comb lines, but at the sacrifice of a severely degraded optical-signal-to-noise ratio (OSNR), as shown in Fig. 1(b), which is a kernel issue, especially when the comb lines are used to transmit data with an advanced modulation format.

We note that the technique of an optical injection locking (OIL) laser can be a candidate method for power amplification and equalization of DKS microcomb lines[10,11], as shown in Fig. 1(c). Particularly, the output DKS microcomb can be demultiplexed, and each comb line is sent into an individual slave laser to achieve OIL at a proper injection ratio, during which the frequency and phase of each comb line are copied to the slave laser whose power is orders of magnitude higher than the original master comb tone. Equivalently, via OIL, the microcomb lines can be substantially amplified without causing degradation of their linewidth and OSNR, since no sizable amplified spontaneous emission (ASE) is introduced within the slave laser during OIL. Also, unlike the EDFA that magnifies all comb lines at once and approximately conserves their original power envelope, the output power of each OIL laser can be individually adjusted to the same value regardless of their original power ratios. To this extent, even multi-soliton state microcombs with a largely uneven spectrum envelope can possibly be equalized via OIL lasers[6,12], thus relaxing the challenge of mandatory access to single-soliton states[12]. Besides, with the fast development of hybrid integration lasers, the OIL method offers an opportunity to put the master DKS microcomb, slave lasers, and data modulators onto a single chip [see Fig. 1(d)], constituting on-chip high performance optical transmitters, so as to implement chip-scale high-performance optical transmitters.

In this work, for the first time, to the best of our knowledge, we demonstrate low-noise power amplification and equalization of DKS microcomb lines via OIL of low-cost distributed feedback (DFB) lasers. The optical power of DKS microcomb lines can be amplified by 30 dB (from −30 dBm to 0 dBm) while maintaining an OSNR larger than 60 dB. Also, we show that when two adjacent comb lines are simultaneously used to lock two individual slave lasers, their mutual frequency and phase coherence can be excellently conserved by the slave lasers. Moreover, the amplified DKS comb lines via OIL are adopted to implement coherent optical transmission over a 100 km fiber link, much better data receiving performances are obtained in comparison with traditional EDFA-based comb power enhancement, confirming the strength of the proposed OIL scheme.

2. Results and Discussion

Figure 2(a) shows the detailed setup of our experiment. In our experiment, a high-Q WGM micro-rod is employed as the Kerr nonlinear cavity, which is fabricated by CO_2 laser beam machining on a rotating silica rod[13,14], as illustrated in Fig. 2(b). The diameter of the micro-rod resonator is about 2.7 mm, corresponding to an FSR of about 21.5 GHz. For DKS generation, a 20 mW pump laser with a short-term linewidth of about 1 kHz is adopted and coupled into WGM resonator via a tapered fiber. To meet the conditions of DKS comb generation, the cavity Q-factor and mode spectrum are optimized by adjusting the sidewall shape of the micro-rod, spatial gap between the micro-rod and tapered fiber, as well as the polarization of

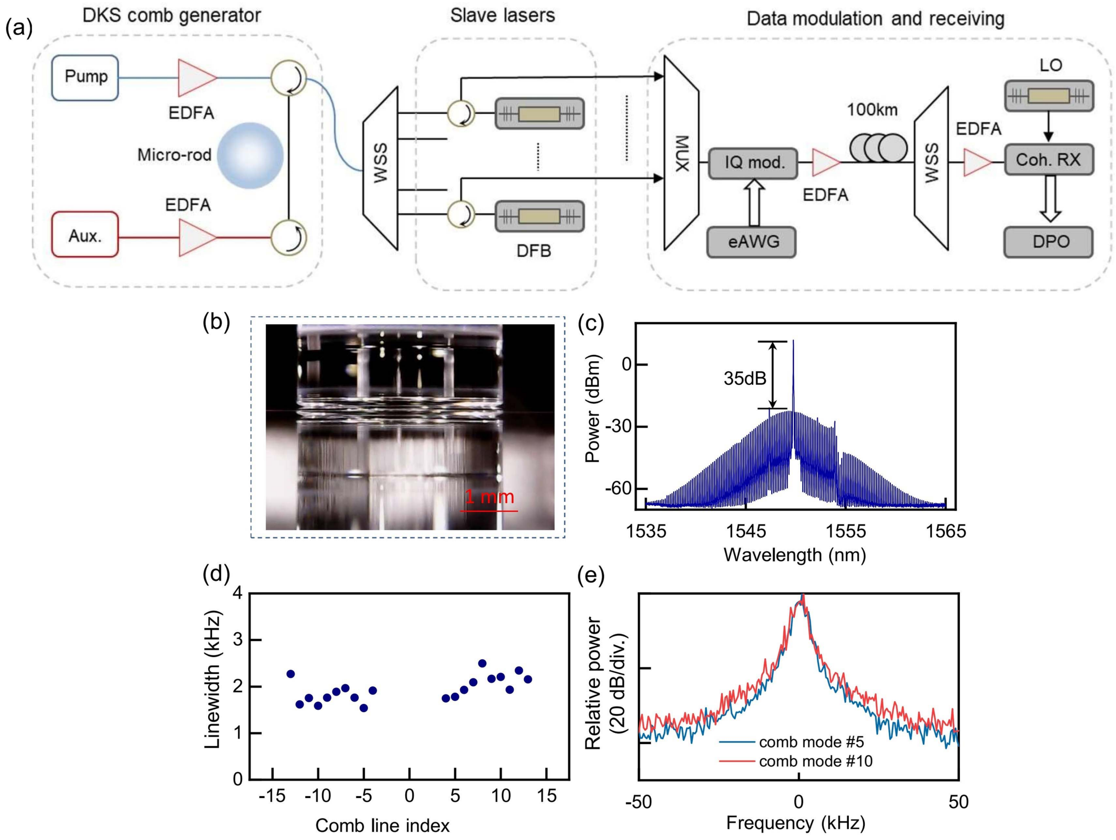

Fig. 2. Characterization of a DKS microcomb generated in a WGM microcavity. (a) Experimental setup for DKS microcomb generation, linewidth measurement, laser injection locking, and coherent data transmission. (b) Microscopy image of WGM micro-rod resonator used in experiment. (c) Optical spectrum of a single-DKS comb state generated in a WGM micro-resonator. (d) Measured linewidths of 20 DKS comb lines adjacent to the pump laser. (e) Self-heterodyne interferometer beat note spectrum measured for the exemplified comb lines #5 and #10.

incident pump light. In the experiment, our patent auxiliary laser heating method is adapted to overcome the thermal effect of the microcavity and stably access single-soliton states[5,15]. The optical spectrum of the generated single-DKS comb is shown in Fig. 2(c), exhibiting a smooth sech^2 envelope whose 20 dB bandwidth is about 16 nm (a minor dip near 1555 nm is caused by avoided mode crossing). Moreover, according to the theory of the DKS microcomb, all of the comb lines are supposed to have identical linewidths with the pump laser. To investigate this, 20 comb lines within 1547.3 to 1552.2 nm are filtered out for linewidth measurement via the delayed self-heterodyne interferometer method[16]. As summarized in Figs. 2(d) and 2(e), the linewidths of all 20 comb lines are below 2.5 kHz, slightly larger than the nominal value of the pump laser linewidth (i.e., $\sim$1.0 kHz). Such linewidth degradation of the generated comb lines with respect to the pump laser is attributed to the random fluctuation of the soliton repetition rate, which is impacted by random pump detuning drift, high-order dispersion, dispersive cavity decay, and avoided mode crossings[17–19], and can be suppressed via various techniques such as Pound–Drever–Hall (PDH) locking of the pump frequency to the cavity resonance[20], or operating the DKS microcomb at the ‘quiet point’[21]. Yet, such mild linewidth degradation can hardly influence data communication in most cases.

Importantly, the total output optical power of the DKS microcomb is about -8.0 dBm, equal to a conversion efficiency of about 0.8%, and even the largest comb lines (adjacent to the pump laser) only have a power level of about -20 dBm, which is far from enough when used as high bitrate data carriers. Especially, as those in-phase (I) and quadrature (Q) modulators used in a coherent transmission system usually feature high insertion loss due to their inner structure, the required optical power of laser tone input into an IQ modulator should be no less than 0 dBm. Namely, our DKS comb lines should be amplified by at least 20 dB to meet the power requirement of a coherent transmitter.

Next, we experimentally investigate OIL-enabled amplification and equalization of the generated DKS comb lines. As previously reported, OIL of a semiconductor DFB laser can be achieved at an injection ratio as low as -50 dB[10,22]. If we set the target output power at $+10$ dBm, theoretically, any DKS comb lines above the power level of -40 dBm can be amplified via OIL. Thus, as can be seen from Fig. 2(c), 81 comb lines within our DKS comb spectrum can possibly be amplified via the laser OIL method. In our experiment, we choose two adjacent DKS comb lines, at 1550.972 nm and 1551.144 nm, respectively, as the master laser tone to study the OIL-based power lift performance. These two comb tones are filtered out by using a wavelength-selectable switch (WSS) and then injected into two discrete slave DFB lasers. The wavelengths of the slave lasers are thermally tuned close enough to the wavelengths of the corresponding DKS comb line to achieve and maintain stable injection locking. As shown in Figs. 3(a) and 3(b), the powers of both comb lines are amplified from −30 dBm to 0 dBm, showing excellent features of high gain and low noise. It can be seen that the amplified comb lines exhibit outstanding OSNR of larger than 60 dB; as will be discussed later, such high OSNR is crucially beneficial for data transmission. Of note, compared with the master comb lines output from the WSS filter, the residual components from the adjacent comb modes are rejected during OIL, implying that OIL can also serve the filtering function and replace the WSS[10,23] if the number of picked-up comb lines and corresponding power splitting factor are acceptable in the specific application scenarios. To compare the performance of the OIL scheme with the traditional EDFA scheme, these two comb lines at 1550.972 nm and 1551.144 nm are also amplified by using two-stage EDFAs. As shown in Fig. 3(c), in contrast to the OIL lasers, the OSNR factors of EDFA amplified comb lines are severely degraded to about 20 dB, due to the accumulation of ASE within the two-stage EDFAs (mainly in the first stage, as the initial comb line powers are too low).

Furthermore, as shown in Figs. 3(d) and 3(e), the linewidths of free-running slave lasers and injection locked slave lasers are also measured. It is seen that the slave laser linewidths are significantly reduced from about 300 kHz to about 2.5 kHz, consistent with the linewidths of the corresponding master soliton comb lines [see Fig. 2(d)]. Also, as mentioned above, mutual frequency and phase coherence among DKS comb lines can be imposed onto OIL slave lasers, so that the guard bands that deal with the random frequency drifts suffered by independent laser carriers are minimized, or even support seamless super channel stitching[5]. As shown in Fig. 3(f), we measured the beat note that reflects the phase coherence between the adjacent DKS comb lines. An almost identical beat note linewidth is obtained between the original comb lines and the injection locked slave DFB lasers, indicating that no mutual coherence degradation is introduced during OIL. In particular, in our experiment, the injection ratio is about −25 dB, corresponding to an estimated injection frequency range of about 2.0 GHz. Since the DKS microcomb itself has salient frequency stability inherited from the pump laser, and the slave DFB lasers are precisely temperature controlled, we believe that there is only minor walk-off between the master and slave lasers, explaining their high coherence after OIL and stable OIL operation for hours, with minor residual phase noise that is revealed by the tiny spurs in the beat note of the OIL lasers [Fig. 3(f)].

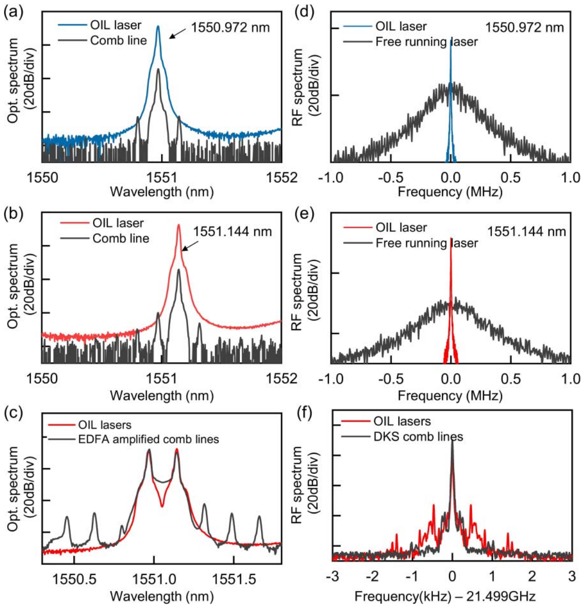

Fig. 3. Characterization of OIL-based DKS comb line amplification. (a), (b) Measured optical spectra of initial DKS comb lines and slave lasers after OIL. (c) Comparison of the optical spectra between OIL slave lasers and DKS comb lines amplified by two-stage EDFAs. (d), (e) Measured linewidth beat note RF spectra of free-running and OIL slave lasers by using the delayed self-heterodyne interferometer method. (f) Comparison of the beat note between two adjacent DKS micro-comb lines before and after OIL.

Next, we demonstrate coherent optical communication by using the power enhanced DKS microcomb lines based on OIL lasers. At the transmitter side, two slave DFB lasers injection-locked by the corresponding DKS comb lines are adopted as the carrier tones and encoded with 18.75 Gbaud 16-quadrature amplitude modulation (QAM) coherent orthogonal optical frequency division multiplexing (CO-OFDM) data signals within a commercial IQ modulator, driven by an electrical arbitrary waveform generator (eAWG) operating at 25 GSa/s. The CO-OFDM symbol is from a 128-point fast Fourier transformation (FFT); 96 subcarriers are used to carry the pilot and data information with the cyclic prefix being 1/16 of the total FFT length. The 16-QAM CO-OFDM signal is transmitted through 100 km standard single-mode fiber. At the receiver side, we use a tunable DFB laser as the local oscillator (LO) to implement coherent data detection within a 30 GHz IQ receiver. The arrived power of each signal channel is about −18 dBm. The down-converted electrical signals are recorded by a 50 GS/s real-time digital phosphor oscilloscope (DPO) and then processed offline using conventional algorithms[5]. The retrieved constellation map and bit error rate (BER) for each of the two data channels are presented in Fig. 4, showing good transmission Q enabled by the high power, high OSNR, and narrow linewidth of the DFB lasers injection locked by the DKS comb lines. On the contrary, when the two comb lines are amplified by multiple-stage EDFAs [as shown in Fig. 3(c)] and used to carry the same 16-QAM data channels, they generate much inferior data Q with unclear constellation maps and unacceptably high BER, as shown in Fig. 4. This simple comparison indicates that the higher OSNR of OIL lasers than the directly amplified comb lines plays an important role in warranting good data transmission performance. Finally, it is worth mentioning that although we demonstrate OIL-based amplification of a 100 GHz DKS microcomb in the present experiment, the microcomb spacing (and, correspondingly, the data channel spacing) can be precisely turned by changing the

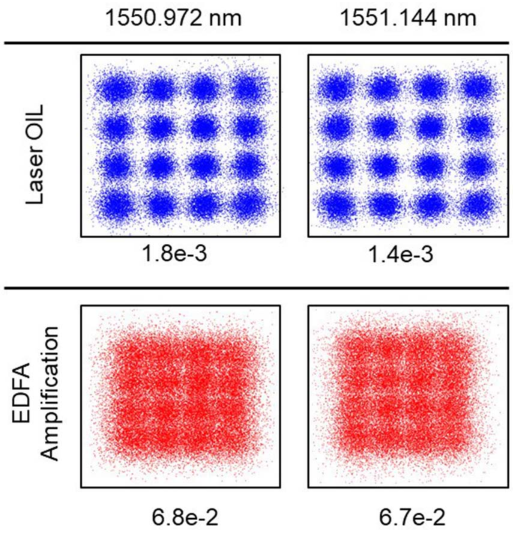

Fig. 4. Comparison between the OIL-based low-noise amplification scheme and conventional EDFA scheme. The constellation diagrams of the received data plotted with blue represent the OIL scheme, and red is for the EDFA scheme. The BER for each channel is listed under each constellation diagram.

radius of the micro-rod resonator during the fabrication process. It had been demonstrated in literature[13] that the FSR of a micro-rod resonator can be changed from 10 GHz to 200 GHz. Also, in our recent publication[14], we showed that via iterative laser annealing, the FSR of a micro-rod resonator can be adjusted with an optimal resolution of <10 MHz.

3. Conclusion

In conclusion, we proposed and demonstrated high-performance DKS comb line power amplification by using the OIL technique. Superior gain factor larger than 35 dB and OSNR performance as high as 60 dB are obtained by injection locking for two DFB lasers using comb lines from a 20 GHz spaced DKS microcomb. Also, thanks to the photon-photon interaction nature of OIL, the superior merits of DKS comb lines, including high-frequency stability, mutual phase coherence, and narrow linewidth, are imposed onto the slave DFB lases. Furthermore, we also demonstrated coherent optical data transmission by adopting the OIL-based method to amplify DKS comb lines and use them as a data carrier, and prominently better performance is obtained from comb power lift via the traditional EDFA-based amplification scheme, confirming the applicability of the proposal. In the present proof-of-concept experiment, we used bulk DFB lasers and passive devices (Mux/Demux, splitter, etc.). However, each of these key modules can find its solution for photonics integration[7,19,23–26]. In particular, given the rapid development of hybrid integrated laser arrays[24,25] and wavelength selective modules[26], our work provides a potential avenue to constitute high-power, low-noise, and multi-color laser sources on-chip.

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