Long-Haul Coherent Transmission Using a Silicon Nitride Microresonator-Based Frequency Comb as WDM Source

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Abstract: We demonstrated transmission of polarization-multiplexed quadrature phase-shift keying data over 6000 km using a low-noise silicon nitride microresonator frequency comb as light source. These results show the technology's suitability for long-haul fiber communications.
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1. Introduction

Optical frequency combs have great potential as light sources in wavelength division multiplexing (WDM) fiber transmission systems. An optical frequency comb can replace hundreds of individual lasers and maintain the channel spacing by controlling its repetition rate. In addition, the broadband coherence of frequency combs can be used to mitigate nonlinear impairments upon fiber propagation [1]. Ideally, the frequency comb should be monolithically integrated with other transceiver components. In this regard, microresonator frequency combs based on silicon nitride offer a promising CMOS-compatible solution for lighting future fiber-communication systems [2]. Recent experiments indicate that the performance of this platform, in terms of optical signal to noise ratio (OSNR) and linewidth, is suitable for coherent communication systems over a few hundred kilometers [3,4].

In this work we demonstrate for the first time that microresonator frequency combs fulfill the requirements for use as WDM light sources in long-haul (>>100 km) transmission links. Specifically, we encoded data using polarization-multiplexed quadrature-phase shift keying (PM-QPSK) at 12.5 Gbaud on seven neighboring channels and successfully transmitted over more than 6000 km in a recirculating fiber loop. An important difference with respect to previous demonstrations is that the comb dynamics is based on modal interaction in a microresonator exhibiting global normal dispersion [5]. Linear coupling between higher-order transverse modes in the cavity introduces a spectral window of net anomalous dispersion that allows for switching on the comb via modulation instability [5]. As a result, the first oscillating lines correspond to the nearest neighbor longitudinal modes and the comb approaches a low-noise state in a deterministic manner [5,6]. The comb features long-term stability, high OSNR and high output power per line, which are critical to realize propagation over thousands of kilometers. This is the first demonstration of a CMOS-compatible multi-wavelength light source with a performance suitable for long-haul coherent communications.

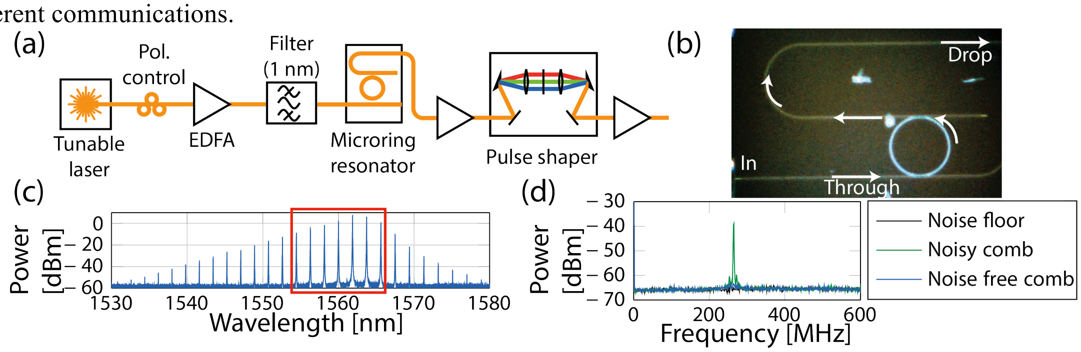

Fig. 1. (a) Sketch of the comb generation setup, including the flattening stage. The OSNR per line after the flattening was measured to be 37 dB at 0.1 nm resolution and the average power 9 dBm per line. (b) Microscope image of the microring. (c) Initial optical spectrum of the comb with 0.01 nm resolution. The lines within the red box were used for transmission. (d) Radio-frequency spectrum with 1 MHz RBW.

2. Experiments

The comb was generated, Fig. 1(a), by pumping a high-Q (>1 million) silicon nitride microresonator (229 GHz free spectral range) with a single 100 kHz linewidth continuous wave tunable laser amplified by an erbium-doped fiber amplifier (EDFA). Assuming 3 dB coupling loss, 24 dBm is coupled into the bus waveguide. Using a filter before the resonator and extracting the comb from the resonator's drop port, see picture in Fig. 1(b), the amount of noise from the EDFA was minimized [7]. The laser approaches the resonance from the high-frequency side (blue detuned) while the noise is monitored with a radio-frequency (RF) spectrum analyzer. The optical spectrum of the resulting comb is shown in Fig. 1(c) and the RF spectrum in Fig. 1(d). To illustrate the need of careful pump laser tuning, Fig. 1(d) also contains an example of a noisy comb when the pump laser frequency was incorrect. The seven highest powered lines were then flattened using a pulse shaper.

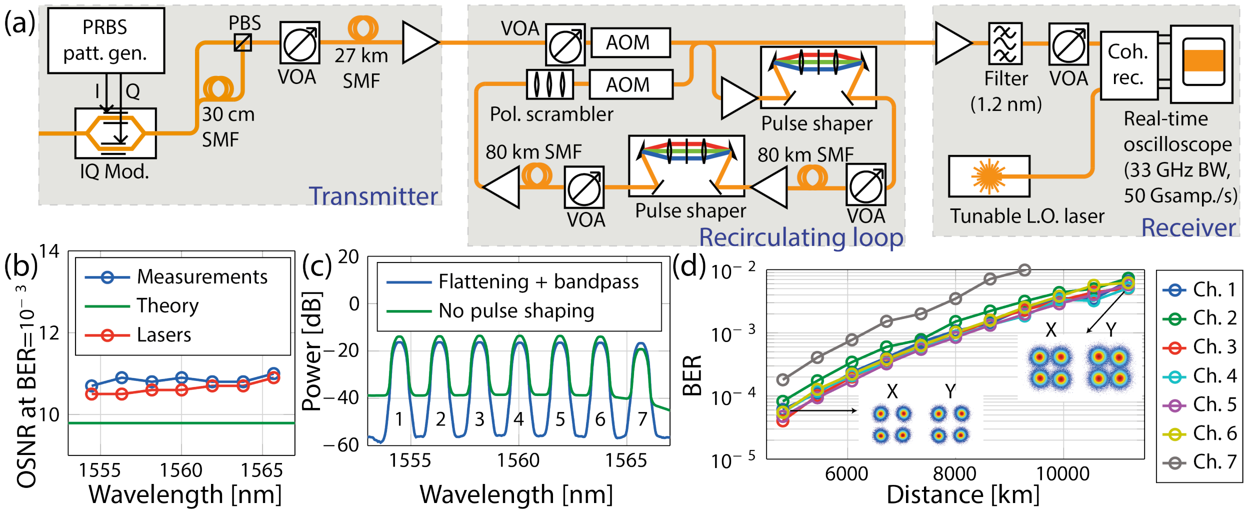

Fig. 2. (a) Sketch of the transmission setup. (b) Back-to-back noise-loading measurements comparing the comb to free-running lasers, showing an average implementation penalty of 1 dB compared to theory. (c) The optical spectrum after one roundtrip with and without pulse shaping at 0.5 nm resolution. (d) BER as a function of propagated distance. The insets show constellation diagrams for line 1 after 4800 km and 11200 km.

The experimental transmission setup is shown in Fig. 2(a). 12.5 Gbaud QPSK data was modulated on all lines using a pseudorandom binary sequence (PRBS) source. A dual polarization signal was generated using a polarization multiplexing emulation stage with a delay longer than 10 symbols. The separate channels were then decorrelated utilizing the dispersion of a 27 km standard single-mode fiber (SMF). Figure 2(b) shows the results from a basic noise-loading measurement showing that the comb does not add significant penalty compared to free running lasers. The long-haul transmission itself was performed using a recirculating fiber loop. One roundtrip contained two spans of 80 km SMF, each of them preceded by a variable optical attenuator (VOA) for setting the launch powers, and a combination of an EDFA and a pulse shaper to ensure that the signal remained flat during the whole transmission. Apart from gain flattening, the pulse shapers also filtered out-of-band noise. Figure 2(c) shows the optical spectrum with and without pulse shaping after one roundtrip. The launched powers were optimized for a transmission distance of 8000 km. The loop also contained a polarization scrambler synchronized to the roundtrip time to ensure that the polarization state into each roundtrip was different and acousto-optic modulators (AOMs) as loop switches. Finally, the receiver consisted of a tunable optical filter for measuring one channel at a time and a coherent receiver with a tunable 100 kHz linewidth laser as local oscillator followed by a real-time oscilloscope. The sampled signal was then fed into an offline DSP algorithm containing IQ imbalance compensation, dispersion compensation, a constant-modulus-algorithm equalizer as well as a Viterbi-Viterbi-based phase tracker.

The calculated BER as a function of distance is shown in Fig. 2(d). It shows that the comb supports transmission over transatlantic distances for a received BER of 10^{-3}, reaching a total data rate of 350 Gbit/s. Channel 7, at 1565.7 nm, suffered a penalty owing to it being located outside the specified gain bandwidth of the EDFAs, leading to a faster accumulation of noise, reaching 6000 km at the chosen BER, while the other channels reached up to 8000 km. These results demonstrate, for the first time, the suitability of this integrated comb technology for long-haul coherent transmission.

3. References

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