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PAPER

Field Trial of Optical Transmission Experiment Employing a Microresonator Frequency Comb Light Source for Low-Latency, Short-Reach Optical Communication

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SUMMARY We present first-time demonstration of short-reach and low-latency optical communication within a real network, employing a microresonator frequency comb as a light source. The modulated signal is transmitted through a 9-km single-mode optical fiber installed in a metropolitan network. This demonstration paves the way for realizing low-latency massively parallel optical communication, which is the key to beyond-5G and 6G network. For a proof-of-concept experiment, we employ an MgF_2 crystalline microresonator with a 20-GHz free-spectral range that could be used for dense wavelength division multiplexing communication. We generated a stable soliton comb and modulated it with simple 10-Gbps intensity modulation and direct detection to achieve a small excess delay of 3.1 µs.

key words: *Microresonator frequency comb, Soliton microcomb, Optical communication, Beyond 5G, 6G*

1. Introduction

The invention of mode-locked fiber lasers and optical frequency combs has resulted in applications to, for example, dual-comb spectroscopy[1], frequency standards[2], and absolute distance measurements[3]. However, their adoption in practical systems, particularly in telecommunications, has been limited by factors such as large size, high cost, and narrow longitudinal frequency spacing. Nonetheless, it has recently been shown that ultra-small optical resonators, which we call microresonators[4], [5], can be used to generate optical frequency combs[6]–[9] on a chip.

Stable mode-locked states, including dissipative Kerr solitons [10], dark pulses [5], and soliton crystals [11], have been successfully demonstrated. These advancements not only ensure low-noise and stable laser output but also, combined with the progress in silicon photonics, hold the potential to facilitate the chip-scale integration of transmitter systems [12].

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The birth of this technology is greatly changing the potential for application because it significantly reduces the size and cost of a multi-wavelength light source, thus making it possible to use optical frequency combs in telecommunication systems[8]. Notably, the longitudinal frequency spacing of these combs is 10 to 100 GHz, which is well suited for use in wavelength division multiplexing (WDM) optical communications[13]. Several optical communications systems using soliton combs, dark pulses, and soliton crystals have already been reported[14]–[17].

Today, the emerging beyond-5G (B5G) and 6G telecommunication infrastructures are starting to require low latency, scalability, and ultra-low power consumption[18], in addition to high speed, a large capacity, and multi-connectivity. Therefore, we need a system with massively parallel programmable network slicing to connect data centers and other metropolitan area sites without high latency[19]. Although network slicing is traditionally realized with software technologies, we need to utilize hardware slicing technologies, by using, for example, optical WDM, to fulfill the demand for low latency for B5G and 6G. In the 1990s, the preparation of 10,000 to 100,000 channels per site was proposed for a hypermedia optical information network[20]. At that time, WDM/TDM (time division multiplexing) and WDM/SCM (subcarrier multiplexing) were candidates for supporting several tens of Mbps/ch because latency was not an issue.

In contrast, the B5G era requires the provision of 10,000 channels at a Gbps/ch speed with ultra-low latency[21]. Since TDM is not a candidate, we need to realize massive parallelism by wavelength, polarization, and spatial division multiplexing. Although the required number of channels is large, it is within our reach if we utilize new technologies, such as a microcomb as a massive-parallel multi-wavelength light source. We do not require a large bit rate for each channel, but we need many channels with several tens of Gbps/ch, thus allowing us to obtain reconfigurability. Owing to their distinct advantage of a chip-scale footprint, microcombs are particularly suitable for high-capacity, low-cost WDM communication systems in the next generation[12].

In contrast to previous demonstrations using state-of-the-art high modulation formats like 64 QAM (quadrature amplitude modulation) in an installed fiber [16], we focus on intensity modulation and direct detection (IM-DD) to build a simple and low-latency system. A simpler system is more advantageous in leveraging the advantage of the compact light source, which we believe is best suited for short-reach range applications. In other words, combining a microresonator frequency comb with simple IM-DD is the key to fulfilling the demand mentioned in the previous paragraph.

With these requirements in mind, we demonstrate multi-wavelength transmission through single-mode optical fibers installed in our laboratory (40 km) and a metropolitan network (9 km) using a soliton microcomb as a light source. We employ a magnesium fluoride (MgF_2) microresonator to enable us to realize a denser channel spacing (i.e., narrower longitudinal spacing) and to use the bandwidth effectively. We use IM-DD and attempt to demonstrate a bit-error rate (BER) of lower than 10^{-9} at a large number of wavelengths. This will make it unnecessary to use forward error correction (FEC) and additional digital processing, which are usually used in digital coherent transmission and that cause significant latency.

Although a number of studies have already reported massive parallel communication using microcombs[8], [14]–[17], [22], they have usually been conducted only in a laboratory environment. It is vital that we attempt a demonstration in a commercially installed optical fiber system if we want to move the technology nearer to commercialization. In this work, we will prove that a microcomb system is capable of being used with existing commercial fiber networks.

2. Design

We employ soliton microcombs because they have much lower noise than other states. However, we need to design the microcomb carefully to achieve error-free transmission because the output power is limited. The comb line power of each wavelength component of a soliton comb is given by[17], [23],

$$P(\Delta\omega) = -\frac{\pi c}{2}\frac{\eta A_{\mathrm{eff}}}{n_2}\frac{\beta_2 D_1}{Q}\mathrm{sech}^2\left(\frac{\pi\tau}{2}\Delta\omega\right) \qquad (1)$$

where $\Delta\omega$ is the relative frequency of the pump, η is the coupling ratio, A_{eff} is the effective mode area, n_2 is the nonlinear index, $D_1/2\pi$ is the resonator FSR, τ is the pulse duration. Since we want to demonstrate WDM at a channel spacing denser than 20 GHz, we use an MgF_2 microresonator with an FSR of $D_1/2\pi = 20$ GHz. The resonator dispersion is $\beta_2 = -6.6$ ps^2/km, which corresponds to an anomalous dispersion[24]. The maximum line power is $P_{\mathrm{max}} = -21.7$ dBm, and the loaded Q is 5.1×10^8 according to Eq. (1). The power is sufficiently high to achieve error-free transmission[17].

3. Experiments and PoC demonstration

3.1 Microcomb generation

We first generated a soliton microcomb with an MgF_2 microresonator. The spectrum of the generated soliton microcomb is shown in Fig. 1(a) and the cavity is shown in the inset. All of the resonators used in this experiment were fabricated by cutting and polishing. Figure 1(b) is a spectrum measured with an electrical spectrum analyzer, which confirms that the channel spacing of the generated microcomb is 20.05 GHz, and the error from 20 GHz is only 0.25%. If we employ ultra-precision machining, the fabrication accuracy will be further improved[25]. We used a narrow-linewidth (< 0.1 kHz) fiber laser (Adjustik E15, NKT Photonics) as a continuous-wave (CW) pump at 1550 nm. Soliton generation and stabilization are detailed in Ref. [17], [26].

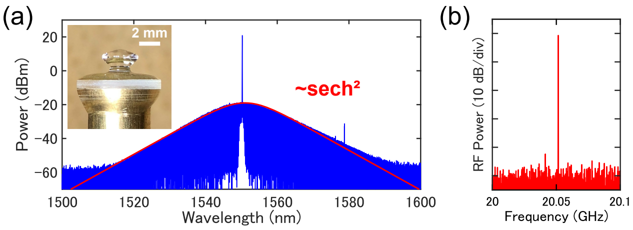

Fig. 1 Soliton comb generation with an MgF_2 microresonator. (a) Optical spectrum of a soliton microcomb. The inset shows a photograph of an MgF_2 microresonator. (b) Electrical spectrum of the beat note of the generated comb showing that the FSR of the resonator is about 20 GHz.

3.2 Transmission experiment in a laboratory

Next, we demonstrated a 40-km transmission experiment in a laboratory environment. The experimental setup is shown in Fig. 2(a). The typical power to pump the microresonator is 0.75 W. The generated soliton comb was amplified, and then the entire comb was modulated by using a single intensity modulator with a $2^{15} - 1$ long pseudorandom binary sequence (PRBS) non-return-to-zero (NRZ) signal. Although it is ideal for modulating each channel separately, we can still obtain information on crosstalk because modes next to each other are all modulated. Separate modulation will be the next step of this research. The entire comb was then transmitted through a 40-km single-mode optical fiber to emulate a WDM transmission experiment but with a much simpler setup. At the receiver end, we selected one of the channels using a band-pass filter (Alnair Labs CVF-300CL), notable for its steep edge roll-off exceeding 1000 dB/nm. The signal was then detected with a commercial receiver (Finisar FTLX1672D3BCL transceiver), which is optimized for 10-Gb multi-rate links over distances up to 40 km of G.652 single-mode fiber. Following this, we proceeded to measure the BER.

We first conducted the following experiment to check whether our setup was compatible with a WDM setup where each channel is normally coded with a different PRBS. Figure 2(b) shows the BER measurement at different modulation speeds ranging from 7.0 to 10.0 Gbps in 0.5 Gbps steps. We employed a microresonator with an FSR of 9.6 GHz for this experiment. The BER degrades as the modulation rate increases, and error-free operation is not achieved at a speed exceeding 8.0 Gbps regardless of the received power. This

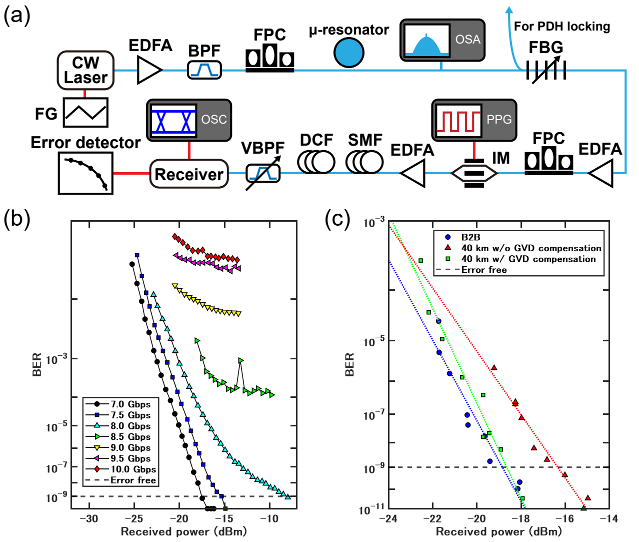

Fig. 2 Transmission experiment in a laboratory environment. (a) Experimental setup for the generation of a soliton microcomb and a multi-wavelength transmission. EDFA, erbium-doped fiber amplifier; BPF, band-pass filter; FPC, fiber polarization controller; FBG, fiber Bragg grating; OSA, optical spectrum analyzer; PPG, pulse pattern generator; IM, intensity modulator; SMF, single-mode fiber; DCF, dispersion compensation fiber; VBPF, variable BPF; OSC, oscilloscope; FG, function generator. The FG is used to scan the wavelength of the laser, which is essential to prepare a soliton comb. The pump is filtered out with the FBG and is used for Pound-Drever-Hall (PDH) locking. PDH locking is a technique for stabilizing the soliton comb generation by feeding the signal back to control the pump laser wavelength. (b) BER at different modulation rates for an MgF_2 microresonator with an FSR of 9.6 GHz. BERs are recorded from 7.0 to 10.0 Gbps in 0.5 Gbps steps. (c) BER measurement using a 20-GHz channel spacing soliton microcomb in B2B and 40-km transmissions. The amount of compensation for GVD dispersion is 27.2 ps.

indicates that the modulation rate needs to be lower than 75% of the FSR for error-free transmission due to the crosstalk between adjacent channels. Since this is what we expect with WDM, we conclude that our simple setup is compatible with the WDM experiments. Therefore, we next performed a transmission experiment using a microresonator with a 20-GHz FSR and modulated the soliton microcomb at a speed of 10 Gbps. Figure 2(c) shows the BER at different received powers for back-to-back (B2B) and 40 km transmissions. We selected a wavelength where the BER was observed to be less than 10^{-9} and proceeded to record BERs by adjusting the received power. Through compensation for the group velocity dispersion, we effectively reduced the power penalty in a 40-km transmission to nearly zero. The dispersion magnitude of the 40-km single-mode fiber is approximately 50 ps, and we compensated for 27.2 ps of it. For this purpose, we utilized a dispersion compensating fiber with a dispersion compensation of −340 ps/nm. This fiber does not provide full dispersion compensation, but our results demonstrate compellingly that comb transmission without a power penalty is feasible through appropriate dispersion compensation.

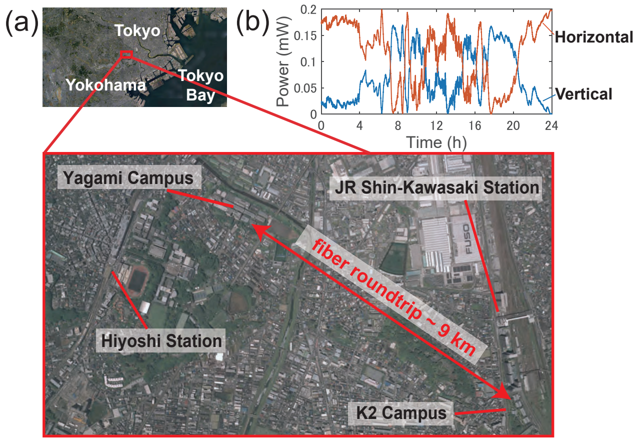

Fig. 3 Field demonstration. (a) Aerial photograph of the area where we installed the SMF. The K2 campus was used as the halfway point. (b) 24-hour measurement of the power of two orthogonal polarizations through the optical fiber. The received signal is split into two linear polarizations (V and H), and the power is recorded.

3.3 PoC field demonstration

For a proof-of-concept (PoC) experiment, we employed IM-DD by using a conventional 12-GHz speed intensity modulator and a 10-Gbps speed receiver, which could be replaced with silicon photonics in the future[12]. A 9-km round-trip commercial SMF was installed via telegraph poles between two university campuses (Fig. 3(a)), where the total transmission loss was 7.5 dB. We first measured the polarization stability for 24 hours, as shown in Fig. 3(b), where rotation was not an issue since we used a simple IM-DD system.

We first proved the low latency of the entire transmission system by measuring it experimentally. Figure 4(a) is the setup for the delay time measurement. We generated a square pulse train with a PPG and then measured it with an OSC.

To obtain the latency of the entire system, we compared the timings of the square waves for those recorded directly after the PPG and that obtained at the receiver after the 9-km transmission. The result is shown in Fig. 4(b), where the difference is 47.9 μs. This value corresponds to the total latency of the entire 9-km propagation system (including fiber transmission and signal processing), and the value is sufficiently small to support B5G and 6G applications. Additionally, to obtain the delays separately, we measured the timings of the square waves for B2B and that after a 9-km transmission and compared their delays. The result is shown in Fig. 4(c), where the delay differences were 44.8 μs. This delay corresponds to the 9-km optical fiber propagation transmission time, which is in good agreement with the simple estimated value. Hence, we obtained an excess delay (a delay that does not include the optical fiber propagation time) of 3.1 μs, and this small value was possible because we avoided using complex signal processing techniques such as digital coherent transceivers and FEC. The primary source of the addi-

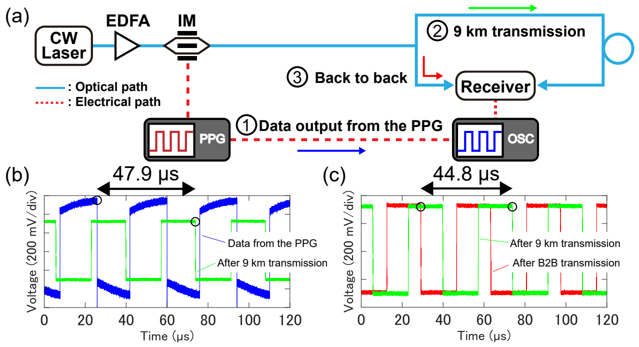

Fig. 4 Small delay measurement. (a) Experimental setup for the delay time measurement. (b) Square pulse trains recorded to measure the latency for a 9-km optical fiber system. The solid blue line is the signal recorded exactly at the output from the PPG. The solid green line is the signal output from the receiver after propagation through a 9-km fiber. (c) Recorded square pulse trains to obtain the delay caused by a 9-km fiber. The red and green lines represent signals after B2B and 9-km transmissions, respectively.

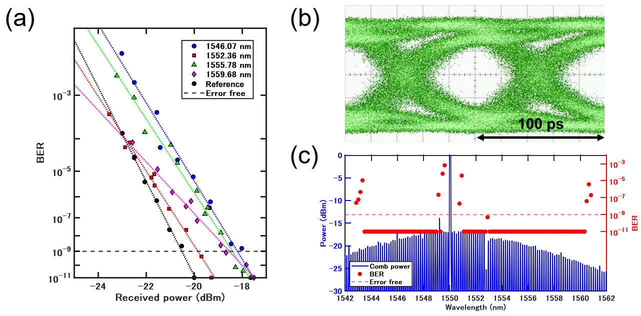

Fig. 5 PoC experiment using a commercial 9-km SMF. (a) BER as a function of the received power at four different wavelengths and with a CW laser after transmission through a 9-km commercial single-mode optical fiber installed between two campuses using a soliton microcomb. The BER, regarded as an error-free operation, is indicated by the dashed black line. (b) Eye pattern when the error-free operation was achieved. (c) The red dots are the best BERs obtained at the corresponding wavelength channel. The blue line is the spectrum of the soliton microcomb. The dashed red line shows the border of error-free operation.

tional delay is attributed to the processing speed involved in the photoelectric conversion at the receiver. Considering that the end-to-end latency stipulated for 6G is under 1 ms [27], the magnitude of this excess delay is indeed minimal, underscoring its negligible impact in practical applications.

Although it may seem evident that the excess latency is small, this is not always the case when employing a digital coherent format with FEC. We have achieved low latency because we use a simple IM-DD format without utilizing FEC. While this technology might seem outdated, it is not when combined with a microresonator frequency comb. This combination allows us to achieve a total transmission speed of Tbps from a single light source by utilizing multiple channels, something not possible with other light sources. High-capacity transmittance with low latency is solely possible with the combination of a microresonator frequency comb and IM-DD without FEC.

Although current mission-critical (MC) applications, such as remote robot feedback control, require a small latency of the order of milliseconds [28] to prevent the system from oscillation, it is predicted that future MC applications, such as gaming and e-sports, will require even smaller latency. We believe our system will even be compatible with such applications.

Next, we measured the BER using the same experimental setup as we used in Fig. 2(a) but with a 9-km optical fiber. Figure 5(a) shows the BER at four different wavelengths of the soliton microcomb in addition to the BER measured with a reference light source, which is the pump laser that we used to generate the frequency comb. In all cases, we achieve a BER of less than 10^{-9}, which is error-free operation. We observed error-free operation at a slightly different power due to the different signal-to-noise (SN) ratio at each channel of the generated microcomb. Figure 5(b) shows the eye pattern when the error-free operation was achieved. We see a clear eye-opening.

Figure 5(c) shows the best-measured BER value at each channel. In the presented spectrum, the blue line shows a detailed view of the soliton comb, while the red plots depict the best-measured BER. We identified error-free operation across 94 channels, specifically within bandwidth ranges of 1543.94 to 1549.30 nm and 1551.08 to 1560.32 nm. Given a modulation rate of 10 Gbps, this translates to a total transmission capacity of 0.94 Tbps.

This PoC demonstration shows that massive parallel (>90 ch) optical communications at a speed of 10 Gbps are possible by using a microcomb. It is the first step towards realizing the reconfigurable hardware network slicing that will make it possible to achieve ultra-low latency. We should note that the PoC is performed by modulating all channels with the same data, but in principle, we emulate the WDM transmission.

Finally, we conducted an extended BER measurement of a single comb line through the field fiber for over 30 minutes, comparing it with the pump laser source as a reference. The results are shown in Fig. 6. In Fig. 6, the red line represents the light power, while the blue line indicates the BER. Specifically, Fig. 6(a) shows the results for CW pump laser, and Fig. 6(b) shows the results when using a single comb line. While we observed wider power fluctuations in the single comb line compared with the CW pump, the BER remained stable in both cases. Notably, there were moments of temporary BER degradation. This is likely attributable to instances where the transmitted signal's clock deviated from the BER detector's clock during its automatic search for the clock and threshold voltage.

4. Conclusion

In summary, we have described a PoC demonstration of low-latency optical communication at a speed of 10 Gbps/ch by using a microcomb through a 9-km round-trip optical fiber installed in a metropolitan network. Such an attempt to exploit microcombs so that they are capable of being utilized in a commercial network is a critical step towards their use

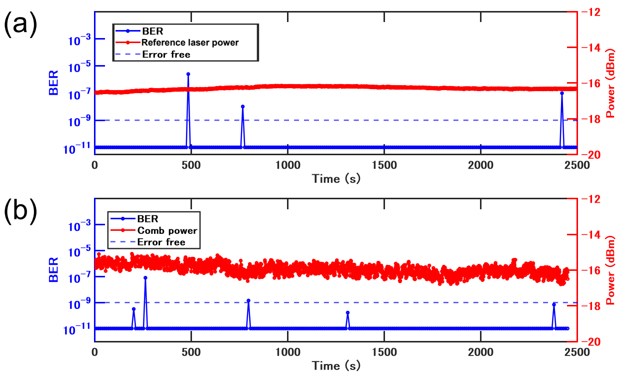

Fig. 6 Long-time BER measurement. (a) BER and power measurement with a reference CW pump laser as a light source. (b) BER and power measurement with a single comb line. The blue line represents the BER and the red line represents the power of the light source.

in an actual system.

The measured total delay of the system was 47.9 µs and the excess delay was just 3.1 µs. Such a small value is possible because we employ a simple IM-DD format without complex signal processing such as FEC with a microcomb source.

The error-free operation was obtained at multiple wavelengths, and the number of parallel transmission channels were 94, corresponding to a total bit rate of 0.94 Tbps. This is the first step towards realizing reconfigurable hardware network slicing, which is the key to meeting the needs of B5G and 6G.

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