110.4 Tbit/s Same-wavelength Bidirectional Optical Fiber Transmission over 100 km G. 654D Fiber in Super-C band with Rayleigh Scattering Noise Suppressed by Raman Amplifiers

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Abstract: we have demonstrated a capacity of 111.6 Tbit/s over a 75-km G.654D fiber along with a capacity of 110.4 Tbit/s over 100 km in super C-band based on the same-wavelength bidirectional optical fiber transmission scheme.

1. Introduction

The demand for high-capacity data transport is in urgent need with the rapid development of high-tech products and services, such as 5G application, virtual/augmented reality and telemedicine. On boosting the capacity of fiber communication systems, numerous methods have been proposed including: advanced modulation format with probabilistic shaping [1], dense wavelength division multiplexing over ultra-wide band [2] and the same-wavelength bidirectional scheme [3-5]. Recent records for capacity in C-band or extended C-band with spectral efficiency (SE) exceeding 10 bit/s/Hz are shown in Fig. 1(a). In [6], the transmitter was configured to deliver 41 x 96 Gbaud DP-PS 256 QAM signal over 100 km fiber achieving 41 Tbit/s capacity on 4.1 THz DWDM spectrum (SE=10 bit/s/Hz). In [7], a total of 34 channels loaded with 130 Gbaud DP-PCS 256 QAM were transmitted over 96.5 km G. 652 fiber yielding a total capacity of 56.51Tbit/s in C-band with a SE of 11.08 bit/s/Hz. In [8], a record of 54.5 Tb/s transmission capacity (SE=11.35 bit/s/Hz) over 48 km fiber realized by a Neural Network-based digital pre-distortion technique has been reported. As an extension of [7], in [9], the bandwidth of the transmitted spectrum was extended to 6 THz resulting in a capacity of 72.64 Tb/s at 12.29 bit/s/Hz over 100 km G. 654D fiber.

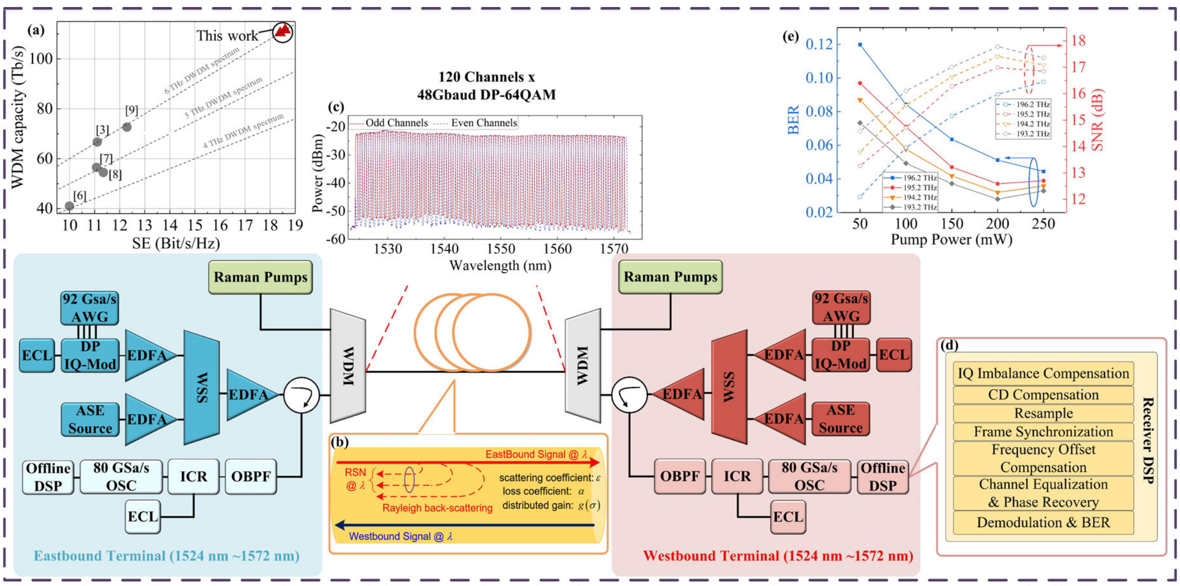

Fig. 1. The experimental setup diagram of the SWB scheme based on DRAs; (a)reported DWDM capacity vs spectual efficiency (SE) exceeding 10 bit/s/Hz; (b) schematic of the transmission and accumulation of the signal and RSN in fibers; (c) 120-channel DWDM transmitted spectrum; (d) the structure of receiver DSP; (e) the measured SNR and BER as functions of pump's power of DRAs.

So far, the schemes mentioned above were all based on unidirectional fiber communication systems. Actually, the same-wavelength bidirectional (SWB) scheme is a relatively promising communication structure to further increase the capacity of single-fiber communication. However, SWB systems severely suffer from the interferences originated from the Fresnel reflection among optical connectors and the intrinsic Rayleigh scattering noise (RSN) along the fiber [4,5]. In the previous research [3], we eliminated the Fresnel reflection through LFMTS-assisted DSP and proposed the idea of using distributed Raman amplifiers (DRAs) to suppress the RSN demonstrating a transmission of 66.7 Tb/s over 90 km G. 652 fiber in super-C band with a SE of 11.11 bit/s/Hz. By extending our previous work, in this paper, we demonstrated a net bitrate of 111.6 Tb/s (SE=18.6 bit/s/Hz) over a G. 654D fiber with length of 75 km along with a net bitrate of 110.4 bit/s (SE=18.4 bit/s/Hz) over 100 km based on the SWB scheme with the RSN suppressed by DRAs. To the best of our knowledge, this is the highest net bitrate using a single optical line system in C-band.

2. Theory and Experiments

As demonstrated in Fig. 1(b), the RSN is accumulated from numerous Rayleigh back-scattering lights, while the signal travels in a one- way straight route in the fiber. The essential distinction of the accumulation and transmission procedures causes a difference between the impacts of distributed gain and loss on the optical power of the RSN and signal, which has revealed that by modifying the distributed gain along the fiber the RSN might be suppressed. Specifically, the optimal distributed gain shall be derived to minimize the power ratio of the RSN over the signal (RSR), which is written as:

$$RSR = \mathcal{F}\left\{f\left(z\right)\right\} \triangleq \frac{\int_0^L \varepsilon e^{2\int_0^z -\alpha+g(\sigma)d\sigma} dz}{e^{\int_0^L -\alpha+g(\sigma)d\sigma} dz} = \frac{\int_0^{\frac{L}{2}} f(z)e^{-2\alpha z}dz + \int_0^{\frac{L}{2}} \frac{f\left(L/2\right)^2}{f\left(L/2-z\right)} e^{-2\alpha\left(z+L/2\right)}dz}{\varepsilon^{-1}e^{-\alpha L} f\left(L/2\right)} \quad (1)$$

where $f\left(z\right) \triangleq \exp\left(2\int_0^z g(\sigma)d\sigma\right)$ and L is the total length of the fiber; α and ε are the loss and Rayleigh scattering coefficients; $g\left(\sigma\right)$ denotes the distributed gain and satisfies the symmetrical system condition that is $g\left(\sigma\right) = g\left(L-\sigma\right)$. The minimum of RSR can be obtained by setting the derivative of $\mathcal{F}\left\{f\left(z\right)\right\}$ to zero. After deduction, it's found that $\mathcal{F}\left\{f\left(z\right)\right\}_{\min} = \varepsilon L$ when $g\left(\sigma\right) \equiv \alpha$ which reveals that the RSN shall be optimally suppressed under lossless condition. Apparently, the exactly lossless fiber condition is unachievable, but the quasi-lossless fiber condition can be obtained with assistance of the DRAs. Here, experiments have been carried out to demonstrate the SWB fiber transmission with the RSN suppressed by DRAs.

The schematic of experiment is shown in Fig. 1. Both bidirectional transmitters were designed to generate 120 channels in super C-band at 50 GHz spacing with wavelength ranging from 1524 nm to 1572 nm, where 19 channels were monitored and the rest channels were simulated by filtered ASE noise. The channel under test (CUT) was generated by modulating a tunable laser (linewidth < 100 kHz) with a dual-polarization in-phase quadrature modulator driven by a 92 GSa/s any waveform generator, which was configured to deliver 48 Gbaud DP-64 QAM for attaining the higher net-bitrate as possible. The spectrum of CUT was constricted by a raised cosine filter with roll-off factor of 0.1. The booster EDFA before the fiber link was designed to deliver its maximum output power of 21.4 dBm. The optical link between the two circulators was composed of 75 km/100 km G. 654D fibers. In the experiment, four Raman pumps with wavelengths of 1425 nm, 1435 nm, 1455 nm, and 1465 nm were utilized to suppress the RSN. In order to obtain the optimal configuration of pump powers, the BER and SNR of 4 representative CUTs were scanned over 100 km G. 654D fiber, during which the powers of four pumps were set to be equal. The results were depicted in Fig. 1(e). It was found that the pumps' power should be set to 4 x 250 mW for optimally suppressing the RSN, which was followed by the following experiments.

In the receiver end, an optical band-pass filter (OBPF) was performed to suppress the amplified spontaneous emission (ASE) noise. Later, the signal was detected by the integral coherent receiver (ICR), which was connected to an oscilloscope with 3-dB bandwidth of 36 GHz and sample rate of 80 GSa/s. In the DSP at the receiver, the electrical signal was first handled by the in-phase quadrature imbalance compensation algorithm. After the operation of chromatic dispersion compensation and resampling, the frame synchronization algorithm was realized with assistance of specially designed pilot sequences. Then the signal was handled through frequency offset compensation algorithm followed by the multi-input multi-output equalizer integrated with the phase recovery algorithm. Finally, the bit error ratio along with the SNR of the received signal was obtained through demodulation, demapping and decoding.

3. Experimental Results

The experiment results are depicted in Fig. 2. The measured SNR of 19 CUTs under unidirectional and bidirectional transmission over 75 km and 100 km G. 654D fiber were recorded as shown in Fig. 2(a) and 2(b), respectively. Obviously, the SWB scheme suffered from the RSN, but it was effectively suppressed by the DRAs resulting in a SNR penalty of merely around 1 dB over a fiber with length of 75 km along with 2 dB over 100 km. The BER of the 19 CUTs were demonstrated in Fig. 2(c). Due to the influence of the RSN, the quality of signal in the SWB scheme was significantly degraded compared with the unidirectional system, and the degradation grew worse with the extension of transmission distance. Nevertheless, the BER of each CUTs were below the threshold required by 25% FEC. In the DSP procedure at the receiver side, the lowest FEC overhead was chosen to maximize the net bitrate of the system. Additionally, the achievable bitrate was calculated from the measured SNR according to the Shannon's formula. The total capacity of the SWB scheme was calculated by multiplying the average bitrate of 19 CUTs by the total number of channels. As depicted in Fig. 2(d), the SWB experiment has realized a net bitrate of 111.6 Tbit/s (SE=18.6 bit/s/Hz) over a G. 654D fiber with length of 75 km along with a net bitrate of 110.4 Tbit/s (SE=18.4 bit/s/Hz) over 100 km. Noteworthily, there was a gap between the net bitrate and the achievable bitrate as for the SWB scheme, which hinted that the capacity of the SWB system shall be further improved with support of technologies, such as probabilistic shaping and enhanced FEC coding.

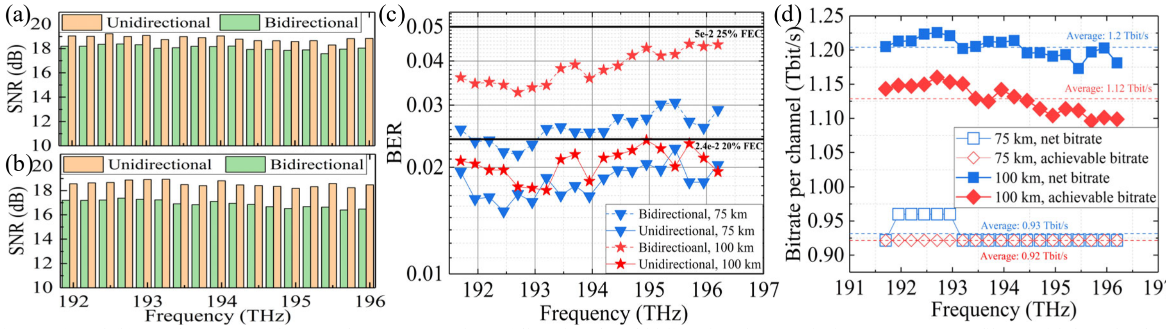

Fig. 2. (a) and (b) are the measured SNR of 19 CUTs under unidirectional and bidirectional transmission over G.654D fibers with length of 75 km and 100 km, respectively, (c) is the achieved BER of 19 CUTs, (d) is the net bitrate and the achievable bitrate of the CUTs.

3. Conclusions

In this paper, the results of super C-band DWDM SWB fiber transmission systems loaded with 120 x 48 Gbaud DP-64 QAM have been presented over 75 km and 100 km G. 654D fiber. A net bitrate of 111.6 Tbit/s at 18.6 bit/s/Hz spectral efficiency over 75-km and 110.4 Tbit/s at 18.4 bit/s/Hz over 100-km have been achieved with the RSN suppressed by DRAs.

4. References

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