First Penalty-free Real-time Co-frequency Co-time Full-duplex Optical Fiber Transmission with 202.1Tb/s Net Capacity Enabled by Hollow-core 5-element NANF

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Abstract: By leveraging extremely-low distributed Rayleigh backscattering in AR-HCF, we report the first real-time 202.1-Tb/s co-frequency co-time full-duplex transmission over a 466-m 5-element NANF based on ultra-wide 12-THz C+L-band EDFAs, exhibiting identical performance to unidirectional transmission.

1. Introduction

Communication between two remote objects is commonly interactive and bidirectional, hence full-duplex communication is always preferred with as low as possible occupancy of resources to enlarge the information capacity. Unlike free-space optical communications which can realize independent counter-propagation of light with the overlapped wavelength, time, and probably others [1], as the most widely-used technology for high-speed and long-haul communications, optical fiber communication can seldom use its dimension of direction without harming other dimensions due to non-negligible Rayleigh backscattering (RBS) of solid-core single-mode fiber (SMF).

Therefore, people usually use two separate fibers to render bidirectional communications at the expense of consuming valuable fiber resources owing to the expensive deployment cost. For other applications requiring strict symmetry, dimensions of time and frequency are always been involved. For example, in commercial PON systems, the counter-propagating upstream and downstream optical signals use different central wavelengths (e.g., GPON uses 1310nm for upstream and 1490nm for downstream) [2]. In high-precision time and frequency synchronization systems, the counter-propagating clock signals can be time-division-multiplexed (TDM) to avoid collision [3]. These two examples have the commonality of low-speed and small quantities of channels. However, for high-capacity long-haul optical transmission systems, the fully-occupied ultra-wide commercial spectrum of 12-THz C+L band [4] leaves no space for co-frequency co-time full-duplex (CCFD) communications in a single-core fiber, otherwise the spectra efficiency should be decreased. So what is the path to break through the bottleneck of true full-duplex in optical fiber imposed by RBS?

In recent years, anti-resonant hollow-core fibers (AR-HCF) have achieved surprising progress in loss reduction [5-7] just like solid-core SMF did 50 years ago. It is worth stressing that the bright prospective of future ultralow-loss AR-HCF partly arises from the inherently low Rayleigh scattering loss of an air-core fiber [8], which hopefully can help the CCFD communication. In 2021, V. Michaud-Belleau et al. experimentally identified an over 40dB lower backscattering coefficient in AR-HCF than in SMF at the same wavelength, with an ultra-low level of -118dB/m [9]. E. N. Fokoua et al. [10] and R. Slavik et al. [11] further clarified different physical mechanisms contributing to the backscattering of HCF in theory and in experiment, respectively. The progress confirms that by replacing SMF with AR-HCF in a coherent communication system, an up to 30 ~ 40-dB reduction in backscattering will unleash direction as a promising independent dimension as any other dimension.

In this work, by combining low-loss (2.25dB/km) AR-HCF and low-loss low-back-reflection (up to -62.47dB) HCF-SMF interconnections, we report the first optical fiber link that truly unleashes the independence of directional dimension. We used commercial 800G coherent optical modules running at OTUC8 (842.065104424Gb/s), newly-commercialized C6T+L6T (covering 102nm, 1524~1626nm) erbium-doped fiber amplifiers (EDFAs) and C6T+L6T wavelength selective switches (WSSs) to successfully demonstrate the first real-time CCFD 202.1Tb/s (2-dir.×120-λ×842.065Gb/s) optical transmission with ultra-wide spectrum and ultra-high-capacity. The CCFD scenario has the same performance as the unidirectional simplex scenario even under such high-speed. Beyond the application in optical communication, the CCFD enabled by AR-HCF may also find significance in other critical and high-value applications, such as quantum key distribution, high-precision time and frequency synchronization, as well as high-precision fiber optic gyroscopes.

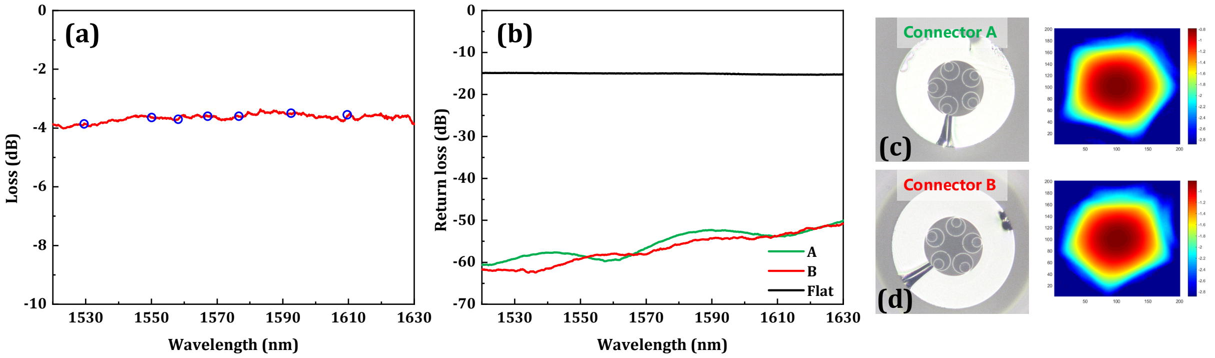

Fig. 1 (a) The loss spectrum of the 466-m NANF-5 link under test; (b) The return loss spectra of the two NANF-SMF angled connectors (in green and in red) and a flat end cut; The microscope graphs of connector end facets and the measured mode field profiles of (c) connector A and (d) connector B.

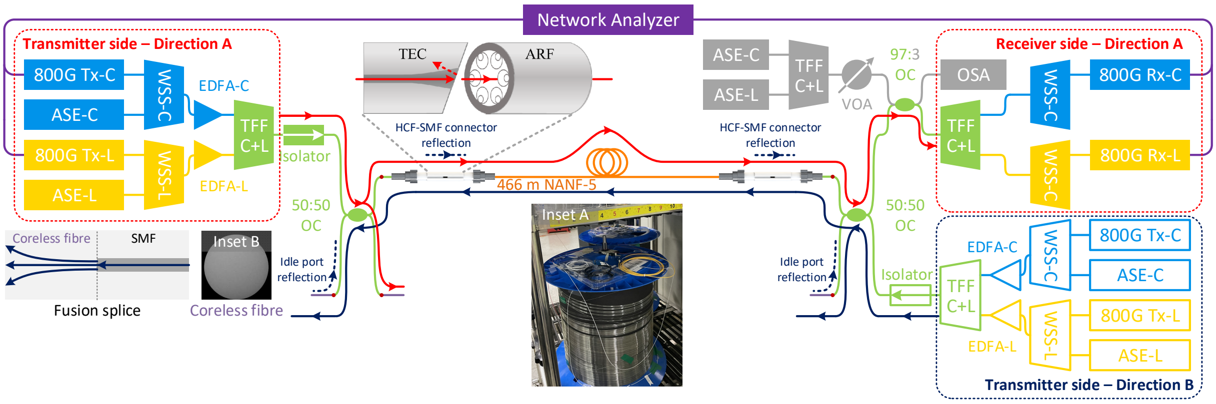

Fig. 2 Setup of real-time 2-dir.×120-λ×842.065Gb/s DP-64QAM-PCS CCFD transmission over the 466-m NANF-5 link; Inset A: The photo graph of the NANF-5 link under test; Inset B: The microscope graph of coreless fiber.

2. Fiber link and Experimental Setup

Fig. 1(a) shows the loss spectrum of the 5-element Nested Antiresonant Nodeless Fiber (NANF [12]) link with a full length of 466m warped around a bobbin with a diameter of 30cm. We make low-reflection interconnections [13] on both sides between the 5-element NANF and the G.652.D pigtail fibers by using an angle-cut thermally expanded core to play the role of mode field adapter and reduced back-reflection simultaneously. Anti-reflection coating is also applied to further mitigate the Fresnel reflection. The measured return losses of the two interconnectors A and B, as well as a flat-cut end, are illustrated in Fig. 1(b). The end facets and the mode fields of the two connectors are measured and shown in Figs. 1(c) and 1(d). We can see that the return losses drop down to -62.47dB in C-band, and about -55dB in L-band. However, the angle-cut will result in a small amount of additional insertion loss (IL). The IL of each connector is about 1.25dB. The overall loss of the link under test is 3.649dB at 1550nm (see Fig. 1(a)). Two 50:50 optical couplers (OC) are used for the combination of two directions, while isolators are settled on each transmitter side to eliminate the backward light. Coreless fibers are also fused to idle ports of OCs for cancelling reflection. So the overall transmission loss increases to about 10.65dB, and it may vary at different wavelengths because the parameters of the OCs, connectors and 5-element NANF are all wavelength-dependent though the difference is very small.

The CCFD transmission setup is shown in Fig. 2. Directions A and B have the same configuration except that Direction B's performance was not measured because of the limitation of both equipment and time. For each direction, two 842.065Gb/s DP-64QAM-PCS real-time optical modules with symbol rate being set to 91.6GBd are used as the transmitters and receivers, each of which is working on the C6T band and L6T band, respectively. The channel grid is 100GHz. The L6T EDFAs have been just commercially available in recent few months, which cover the range of 1575~1626nm with a noise figure (NF) of <8.0dB. It should be noted that currently, there are still no available optical modules, EDFAs and wavelength selective switches (WSSs) that can be continuously tuned over C6T+L6T bands, so two sets of optical devices that work on the C6T and L6T bands individually are employed. Two sets of 100GE modules and ethernet analyzers (VIAVI ONT 603) are utilized for error checking after transmission and forward error correction (FEC). Two amplifier spontaneous-emission noise (ASE) sources are used

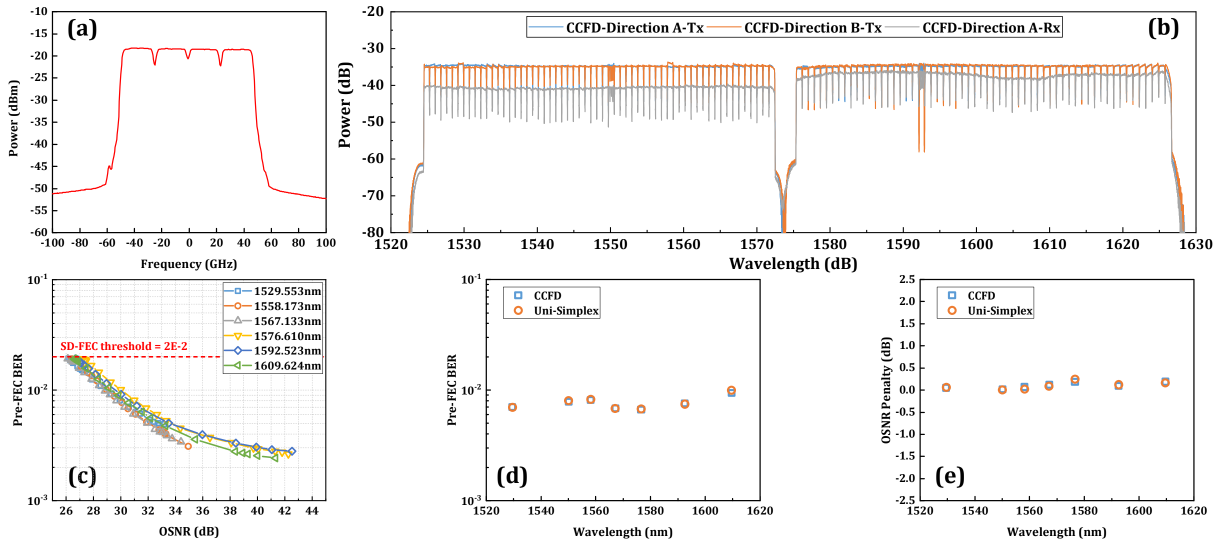

Fig. 3 (a) The spectrum of the 842.065Gb/s optical module used in our test; (b) The measured spectra of the transmitting side and receiving side of both directions; (c) The measured pre-FEC BER versus OSNR curves of 6 measured channels; The measured (d) pre-FEC BERs and (e) OSNR penalties of all 7 channels for both SWB-FD and Uni-Simplex.

for emulating all the other vacant channels in both the C6T band and L6T band, respectively. The two 800G signals and dummy channels are combined by the two WSSs and boosted by two EDFAs. Then a band multiplexer (MUX) will further combine the two bands and launch them into the link under test.

3. Experimental Results

Fig. 3(a) shows the spectrum of the 842.065Gb/s optical module used in our test. To fully exploit the performance across the 12-THz band, we choose 7 channels, i.e., 1529.553, 1550.116, 1558.173, 1567.133, 1576.610, 1592.523, and 1609.624nm for measurement, respectively. The measured bit error rate (BER) versus optical signal to noise ratio (OSNR) curves of 6 wavelengths are illustrated in Fig. 3(c). It can be seen that though only two modules used in test, the tuning of wavelength can still affect the performance of the modules. The measured spectra of the transmitting side and receiving side for Direction A and the transmitting side for Direction B in our test are shown in Fig. 3(b). The spectra at both transmitting sides are trimmed by WSSs to flat responses. Pre-FEC BERs and OSNR penalties of all 7 channels in CCFD and unidirectional simplex transmission are measured for comparison. As shown in Fig. 3(d-e), for each channel, CCFD transmission and unidirectional simplex transmission have extremely close performance with each other.

The overall net capacity of this experiment is up to 202.1Tb/s with negligible penalties over the 12-THz ultra-wide C6T+ L6T bands by using real-time 842.065Gb/s DP-64QAM-PCS optical modules. To the best of our knowledge, it is the highest capacity ever realized in HCF links with real-time commercial equipment rather than offline experiments. The previous capacity world record is produced in a multi-mode 37-cell photonic bandgap HCF [14] with gross capacity of 73.7Tb/s (net capacity 57.6Tb/s).

4. Conclusions

In conclusion, we report the first CCFD ultra-high-capacity optical fiber communication system based on AR-HCF. By using AR-HCF's drastic suppression to distributed Rayleigh backscattering, we successfully demonstrate a 202.1-Tb/s CCFD transmission over a 466-m AR-HCF based on commercial 800G optical modules and ultra-wide 12-THz C+L band, which exhibits identical performance to unidirectional transmission. For the first time, we liberate the two propagation directions as harmless physical dimensions for fiber optical communications with the high capacity feature.

5. References

[1] W. Li et al., *Optics Lett.*, **47**(24), 6389, 2022.
[2] ITU-T G.984.2 GPON, 2019.
[3] Y. Yuan et al., *Chin. Phys. B*, **26**(8), 080601, 2017.
[4] M. Zuo et al., *ECOC 2023*, **M.A.5.3**, 2023.
[5] S. F. Gao et al., *Nat. Commun.*, **9**(2828), 1, 2018.
[6] G. T. Jasion et al., *OFC 2020*, **Th4B.4**, 2020.
[7] G.T Jasion et al., *OFC 2022*, **Th4C.7**, 2022.
[8] E. N. Fokoua et al., *Adv. Opt. Photonics*, **15**(1), 1, 2023.
[9] V. Michaud-Belleau et al., *Optica*, **8**(2), 216, 2021.
[10] E. N. Fokoua et al., APL Photonics, **6**, 096106, 2021.
[11] R. Slavík et al., *Optics Express*, **30**(17), 31310, 2022.
[12] F. Poletti et al., *Optics Express*, **22**(20), 23807, 2014.
[13] D. Suslov et al., *Optics Express*, **30**(20), 37006, 2022.
[14] V. A. J. M. Sleiffer et al., *J. Light. Technol.*, **32**(4), 854, 2014.