

First Demonstration of Hollow-Core-Fiber Cable for Low Latency Data Transmission

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Abstract: We present the first field-deployable hollow-core-fiber (HCF) cable and successfully demonstrate an error-free transmission of direct-detection 10Gb/s DWDM signals over a 3.1km cascaded HCF cable link, enabling 31% latency reduction compared to solid-core-fiber cable.

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1. Introduction

There is increasing interest in low latency optical communications [1-3] for time-sensitive applications including high frequency trading, high performance computing, remote operation and control for offshore oil-gas recovery, 5G x-haul mobile networks, and intra-data center interconnection. Low latency can be achieved by straight transmission line connection, minimization of equipment delay, and optimizing DSP in transceivers, or use of wireless communication. Direct-detection systems without forward-error-correction (FEC) are preferred as FEC and DSP in coherent transceivers add about 5.6 μ s to 9 μ s delay [4]. Hollow-core-fiber (HCF) has been proposed for low latency communication for about 20 years [5]. HCF provides a 1.54 μ s/km (corresponding to 31%) latency reduction at 1550nm compared to solid-core fiber, which is a huge advantage over existing and competing fiber technologies. In recent years, remarkable progress has been obtained in HCF technology, with attenuation reduced to 0.65dB/km in antiresonant HCF [6] and transmission demonstrated over long lengths [3,7]. However, in all previous transmission studies, the HCF was wound on a spool. It is well known that spooled fiber can obscure practical impairments such as macro/micro-bending loss, polarization-mode-dispersion (PMD) and multipath interference (MPI) from modal crosstalk. This can be especially true for HCF, which can be few-moded or suffer from insufficient higher-order mode (HOM) attenuation. Proper evaluation of HCF transmission must therefore be performed with cabled fiber and include the effect of appropriate fiber termination. This is of particular importance for direct-detection system in which low PMD in the cable is critical.

In this work, we demonstrate error-free (bit-error-ratio (BER) $<10^{-15}$) transmission of direct-detection 10Gb/s DWDM signals over a 3.1km cascaded HCF cable link (not spooled HCF). We show attenuation before and after cabling, as well as PMD and chromatic dispersion (CD) characteristics. To the best of our knowledge, this is the first time that a commercialized HCF cable is reported.

2. Hollow-Core-Fiber Cable

There are numerous technical challenges when cabling any large mode area fiber, including hollow-core fiber. As such, our cable uses a loose-tube construction to minimize strain and macro/micro-bending while also meeting the rigors of conventional direct buried and underground duct environments. Each cable span is well terminated with low loss LC/UPC connectors fusion spliced to single-mode fiber (SMF). The cable passed harsh environment testing over the temperature range from -40°C to 80°C . The HCF used in this trial (cross-section shown in the inset of Fig.1a) is an improved version of the fiber presented in [2] with the outer shunt cores from [8] to reduce HOM

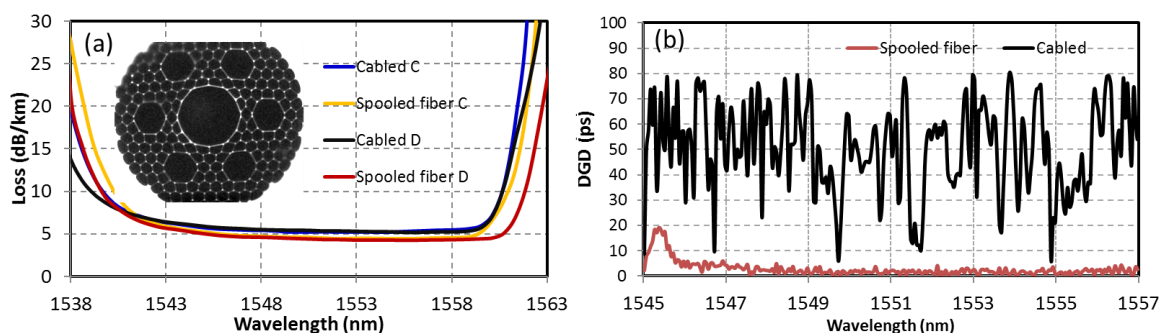


Fig. 1 (a) Attenuation in a HCF before and after cabling, inset: cross-section of HCF, (b) DGD of spooled HCF and cabled HCF when the HCF is not twisted during draw process

content and MPI. The LP_{11} and macrobend attenuation are similar to conventional SMF. Fig.1(a) plots the measured attenuation of the HCF before and after cabling, showing maximum added losses after cabling of less than 0.7dB/km over the 1544.9-1558.6nm operation window.

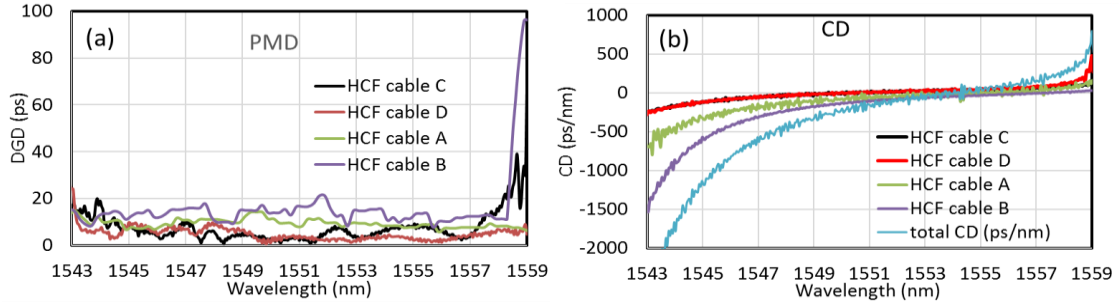


Fig. 2. Measured DGD (a) and CD (b) of the four HCF cables. The cable lengths are specified in Fig.3.

Fig.1(b) illustrates the potential for a misleading measurement when using spooled fiber. Birefringence in all HCFs is difficult to avoid because of the necessary symmetry of the structure surrounding the core. As with early single-mode fiber, PMD is masked by spooling due to perturbations from multiple crossovers along the fiber length. In this case, transmission tests of such a spooled fiber would appear to be successful. In contrast, when cabled, the fiber is relaxed and the intrinsic PMD is unveiled, Fig.1(b), which increases the transmission penalty. Note that while PMD is readily addressed using the conventional method of twisting during fiber draw, MPI due to HOM and surface mode coupling can exhibit similar “spool filtering”. Fig.2(a) shows the measured differential group delay (DGD) of four cables constructed with HCF drawn with draw twist period of the order of 10^{-2} m. The average DGD of cables A-D in the operation window (1544.9-1558.6nm) is 12.3, 8.1, 5.5 and 4.4ps, respectively. Fig.2(b) shows that the absolute value of the chromatic dispersion (CD) is <600 ps/nm in the operation window.

3. Transmission Experiment

To assess the low latency transmission performance of HCF cables, we conducted a 10Gb/s direct-detect non-return-to-zero (NRZ) DWDM transmission experiment. As shown in Fig.3, 35 DFB diodes with 50GHz channel spacing from 1544.92nm to 1558.58nm are used, and odd and even channels are multiplexed and separately modulated by two Lithium-Niobate (LN) modulators with 10Gb/s 10^{31} -1 PRBS from a pattern generator. The combined odd and even channels are amplified by an EDFA, then launched into the HCF cable link, which consists of two 0.59km and two 1km HCF cables, connected by LC/UPC connector. The total link loss at 1550nm is about 30dB, and about half this loss is from splices and connectors between cables. The 35 channels are amplified before being de-multiplexed. The selected channel is sent to a 10Gb/s clock data recovery (CDR) receiver. An ASE source is added with a variable optical attenuator (VOA) by a 20/80% coupler to evaluate the transmission performance of the HCF cable. The BER is measured with a BERT. The inserts in Fig.3 shows the transmitted (a) and received (b) signal spectra.

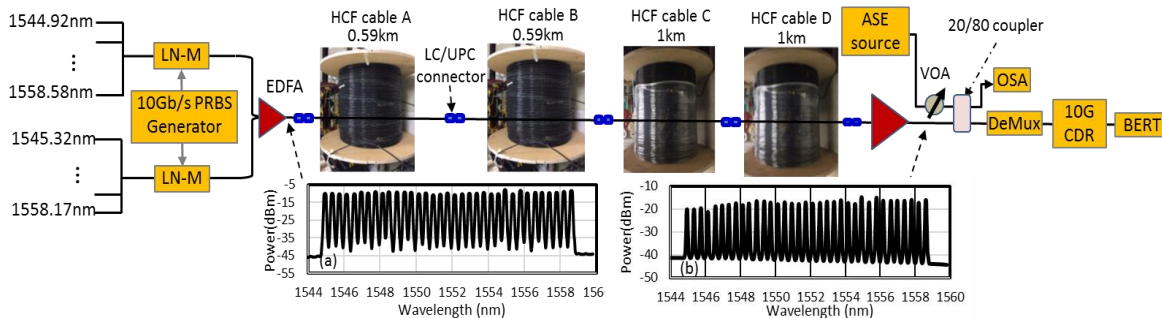


Fig.3. Experimental set-up, (a) transmitted spectrum, (b) received spectrum

The BER vs. required optical signal-to-noise ratio (OSNR) is measured for both back-to-back and a 10Gb/s 3.1km HCF cable link. The BER is directly counted from the BERT if the BER is larger than 10^{-12} , while if the BER is lower than 10^{-12} , it is measured through a decision-circuit method of measuring the Q-factor [9]. Fig.4 (a) shows an example of the BER vs. decision threshold for a Q-factor of 18.1dB. Fig. 4 (b) plots the BER vs. OSNR for two examples of middle channels at 1550.12 and 1555.75nm, and four channels near the edges of the operation window. BER $< 10^{-15}$ can be obtained for wavelength channels from 1545.32nm to 1558.17nm (totally 33 channels). Most

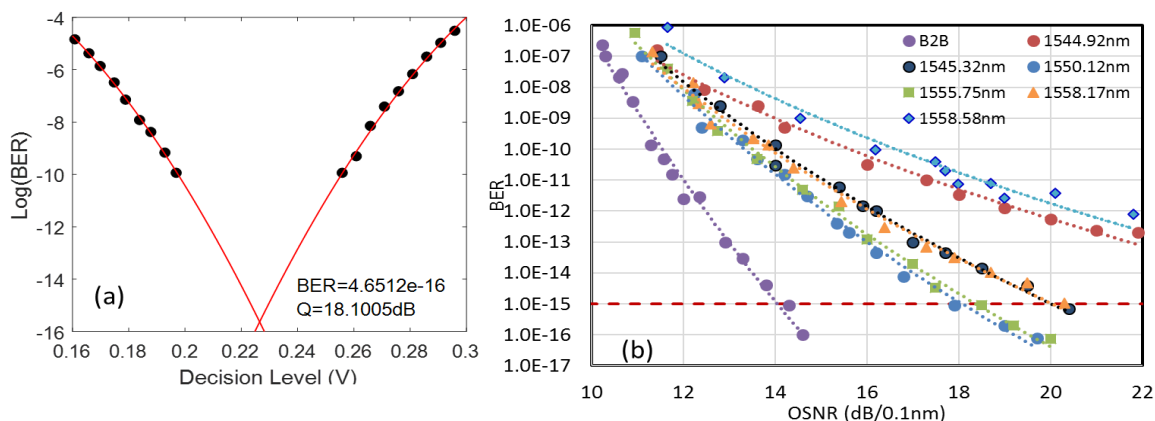


Fig. 4. (a) An example of the BER vs decision threshold, (b) BER vs OSNR for back-to-back and six transmission channels

transmission channels have an OSNR penalty of 4 ~5dB at a BER of 10^{-15} , and up to 6dB for channels near the edges. However, BER floors were observed for the transmission channels at the edges 1544.91nm and 1558.58nm. The short wavelength channel 1544.91nm has a large penalty from CD, while the longest wavelength channel 1558.58nm has a large penalty from PMD, as seen in the received eye diagrams shown in the insets of Fig.5. The measured average received OSNR for all channels is about 24.5dB/0.1nm. To assess the system OSNR margin, the BER of all 35 channels were measured at OSNR 20dB/0.1nm by adding ASE before the receiver. Fig.5 plots the BER as a function of wavelength channels. Error-free ($BER < 10^{-15}$) transmission was achieved for 33 channels from 1545.32nm to 1558.17nm at an OSNR of 20dB/0.1nm, resulting in 4.5dB/0.1nm average OSNR margin. Eye diagrams for two channels at the edges and a middle channel at 1551.72nm are also shown in inset of Fig.5.

4. Summary

We have demonstrated error-free transmission of 33 direct-detection DWDM channels at 10Gb/s over a 3.1km cascaded HCF cable link. We have described the properties of the HCF cable including attenuation, PMD and CD. This distance and data rate are relevant to several immediate commercial applications. To the best of our knowledge, this is the first time that a commercialized HCF cable has been presented.

5. References

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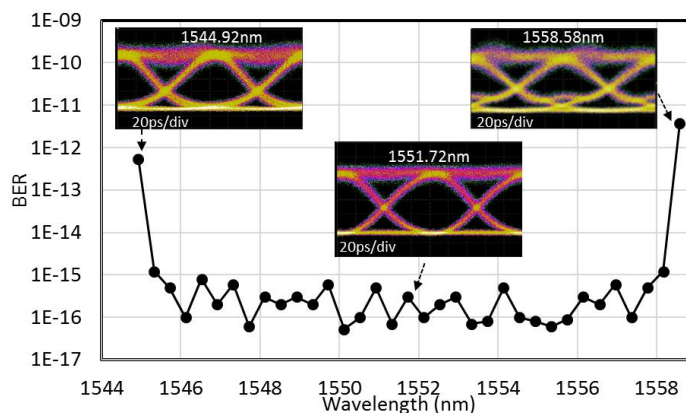


Fig. 5. BER as a function wavelength channels for received OSNR 20dB/0.1nm, BER below 10^{-15} were obtained for 33 channels from 1545.32 to 1558.17nm