Simultaneous Distribution of Stable Frequency and Data Signals Over Hollow-Core Optical Fibers

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***Summary*—We demonstrate the simultaneous distribution of stable frequency and data signals over hollow-core fibers (HCF). We show that the use of HCF reduces frequency stability degradation observed in links made of standard single-mode fibers (SMFs) due to nonlinear interaction between the co-propagating signals which is orders of magnitude weaker in HCF.**

Keywords*—*Frequency distribution; Telecom data; Hollow-core fibers

I. Introduction

Besides data transmission, standard single-mode optical fibers (SMFs) have also been used in a variety of applications, including stable frequency transmission. In this application, it offers a frequency stability that is several orders of magnitude better than those achieved with satellites. Some of applications benefiting from this improved stability include the Square Kilometer Array (SKA) for radio astronomy [1] and terrestrial positioning [2] that can enhance global navigation satellite systems (GNSS) in urban areas. Such applications also require the distribution of data, ideally transmitted over the same fiber infrastructure as the stable frequency signals. Such simultaneous transmission is required for cost-effective deployment, however, for optimum performance, the interaction between these signals needs to be managed [3]. In particular, the stable frequency signal is prone to degradation due to such an interaction, as even a small amount of amplitude or phase jitter can significantly deteriorate its stability [4].

The interaction between signals is mainly due to the nonlinear interaction in the silica glass (e.g., Kerr effect) through which the signals propagate in SMFs. The main nonlinear interactions are cross-phase modulation (XPM) and four-wave mixing (FWM) between the co-propagating signals, effectively adding noise [5]. This signal degradation depends on the distance, number of nodes, etc. There are several approaches to reduce the nonlinear interactions such as increasing wavelength separation between channels, use of unequal wavelength spacing [6], use of optimized modulation formats [6], or decreasing the launched optical powers [3]. These approaches, however, introduce various tradeoffs, e.g., an increase in wavelength separation reduces the maximum capacity of data transmission (as fewer data channels can be transmitted), while reducing optical powers limits the transmission distance and requires more optical amplifiers.

Here, we propose to use a new generation of optical fiber, namely hollow core optical fiber (HCF), in which light propagates through the central hole rather than silica glass, providing 3-4 orders of magnitude lower nonlinearity [7]. Thanks to this low nonlinearity, signals sent through a HCF can have significantly higher optical powers than when sent through an SMF with the nonlinear interaction between channel strongly reduced. HCFs have recently achieved attenuation comparable to that of SMF, specifically so far as low as 0.174 dB/km at 1550 nm [8]. They also offer further advantages over SMFs, for example, they offer more than one order of magnitude lower sensitivity of propagation time to temperature, 8 times smaller chromatic dispersion, 30-40 dB lower Rayleigh backscattering and 30% lower propagation time [9]. Here, we demonstrate how simultaneous distribution of a frequency signal and two DWDM data signals is improved when sent over an HCF as compared to the SMF.

II. Experiment and Results

We used a 4.3-km long HCF with the Nested Antiresonant Nodeless Fiber (NANF) geometry [7] and a similar length of SMF (4.4 km) for comparison. The HCF attenuation was measured to be 0.49 dB/km at 1550 nm. SMF pigtails were spliced at the HCF ends resulting in a pigtailed HCF (SMF-HCF-SMF) total loss of 3.6 dB.

To compare the nonlinear interaction in the SMF and HCF used here, we first launched into both samples two 26 dBm cw lasers (total power of 29 dBm) emitting at 1550.1 and 1550.9 nm. Output spectra are shown in Fig. 1, showing that the FWM products in the SMF are -23 dB below the signals, while they are below -45 dB in the HCF, i.e., over 20 dB lower. We confirmed the HCF measurement was actually limited by the FWM in the erbium-doped fiber amplifier (EDFA) used to boost the signal to the 29-dBm level [10].

Our experimental set-up is shown in Fig. 2. The 10 GHz frequency signal locked to a reference generator (Timetech 10292, synchronized to a GPS clock) was used to modulate a commercial tunable laser set to 1549.3 nm with output power of 6 dBm. The two-channel data signals (10 Gbit/s on-off keyed, OOK) were generated at 1550.1 nm and 1550.9 nm (forming together with the frequency signal three signals on a 100 GHz frequency grid). Both data channels were combined via a coupler and amplified with an EDFA. Subsequently, they were combined with the frequency signal using another optical coupler. The power of the transmitted data signals was controlled via controlling the EDFA gain. At the user end, the frequency signal was divided into two parts with one returned back for link stabilization [9] and the other one for frequency stability measurement.

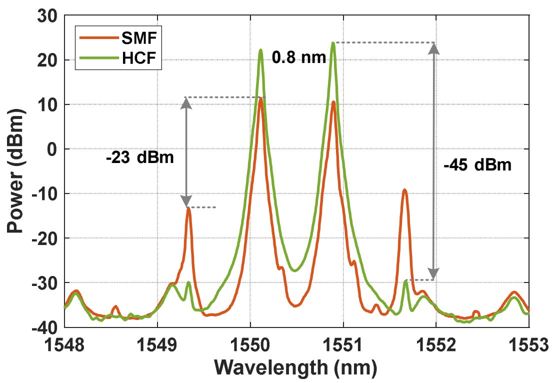

Fig. 1. Measured FWM inside 4.3 km of HCF (green) and 4.4 km SMF (red) when launching two 26-dBm cw lasers. SMF lower output power is due to stimulated Brillouin scattering.

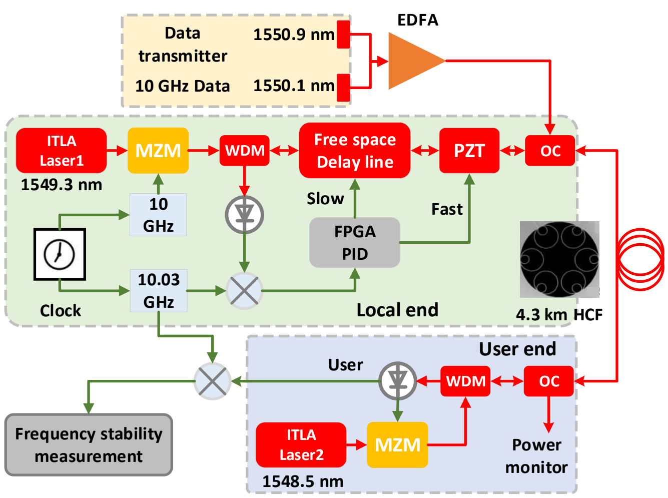

Fig. 2. Experimental set-up. MZM: Mach-Zehnder modulator; WDM: wavelength-division multiplexer; OC: optical coupler. As transmission fiber, we use either 4.3 km of HCF or 4.4 km of SMF for comparison.

After stabilizing the fiber link, we measured how the power of the two data signals influences the frequency signal stability in terms of Allan deviation, which is shown in Fig. 3. We see the stability degraded in the SMF when the power of the data signals increased beyond 12 dBm. For the HCF, the signal did not degrade even when using the full data signal power of 26 dBm. Thus, it is possible to launch at least 26-12 = 14 dB more power into the HCF. Considering HCF has 2.6 dB higher loss than SMF, it is possible to transmit at least 11.4 dB more power with HCF as compared to the SMF without any degradation.

In a practical network scenario, more channels over longer distances may be used, meaning the degradation of the frequency signal will occur at lower powers than the 12 dBm shown here.

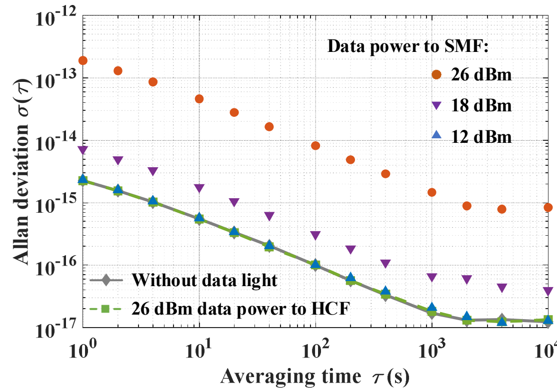

Fig. 3. Measured Allan deviation for frequency signal distributed through HCF and SMF with different input data signal optical power.

III. Conclusions

We present the first experiment showing simultaneous distribution of stable frequency and telecom data over HCF, which enables a strong reduction of nonlinear interactions between these signals as compared to that achievable in SMF. In particular, we showed that in our specific configuration, over 11 dB stronger optical signals could be delivered with HCF over a similar length of SMF without any degradation due to the nonlinear interaction between the signals simultaneously transmitted over the same fiber. Our result points to potential use of the emerging HCFs in metrology applications in which signals of interest are co-propagated with data signals, which is essential for cost-effective implementations.

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