Ultra-high resolution and long-range OFDRs for characterizing and monitoring Hollow-core DNANFs

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Abstract: We demonstrate distributed characterization of hollow-core DNANFs using two OFDR systems: the first reaches 5-km with sub-mm resolution and measures distributed modal birefringence, whilst the second probes over 100-km with 3-m (25-m) resolution at 10-km (100-km) and >90-dB dynamic range.

1. Introduction

Recent advances in the design and manufacture of hollow-core fibers (HCFs), particularly nested and double-nested anti-resonant fibers ((D)NANF), demonstrate that HCFs provide fundamental advantages as a fiber for long-haul transmission systems due to properties such as lower latency, lower (<0.1dB/km) loss, low dispersion, low nonlinearity, low backscatter and wider or alternative wavelength bands [1, 2]. Reliably achieving high levels of performance in mass-produced HCFs requires a high degree of transverse and longitudinal uniformity of the fiber structure. It is known for example that small asymmetries in the position, size and thicknesses of the tubes in the cross section result in fiber birefringence and PMD [3]. However, probing this in a distributed manner, which could enable further fabrication improvements and facilitate practical network adoption, poses a significant challenge because anti-resonant HCFs have 3-4 orders of magnitude lower backscatter compared to single mode fibers (SMFs). Whilst this enables bidirectional transmission, it also severely hinders the capabilities of traditional single-end distributed characterization tools such as OTDR, DAS, and OFDR [4].

Unlike backscatter in solid core fibers which results from Rayleigh scattering in the solid core, HCF backscatter originates from two sources: 1) dynamic scatterers in the form of moving air molecules in the hollow regions and 2) static scatterers in the form of surface roughness. Air molecule backscatter is known to be 27 dB below the Rayleigh levels in solid core fibers, but can be probed with amplified OTDRs. Surface roughness backscatter, being lower by a further 15 dB, is swamped by air backscatter in an OTDR [5]. This much weaker, permanent and static surface scatter can provide insights into the fiber's uniformity and can be probed by coherent reflectometry techniques such as OFDR. This is because the air backscatter is randomly broadened by about 500-MHz and decohers within picoseconds as the constant random motion of air molecules produces Doppler shifts upon reflection. Here, we demonstrate for the first time that this weak (>40dB lower than SMF) sidewall scatter fingerprint can be used to measure the local modal birefringence and thermal sensitivity of HCF via correlations in

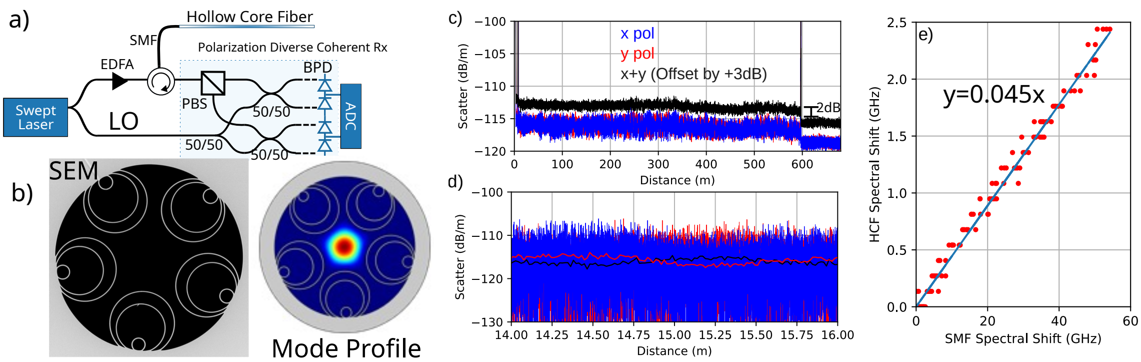

Fig. 1. a) High resolution OFDR using swept wavelength laser scanning 20 nm. b)cross-section of a DNANF and its calculated mode profile. (c,d) Measurements of a 600 m HCF. e) Rayleigh spectral shift comparison between SMF input fiber (circulator output) to HCF as 600-m spool is heated approximately to 50° C.

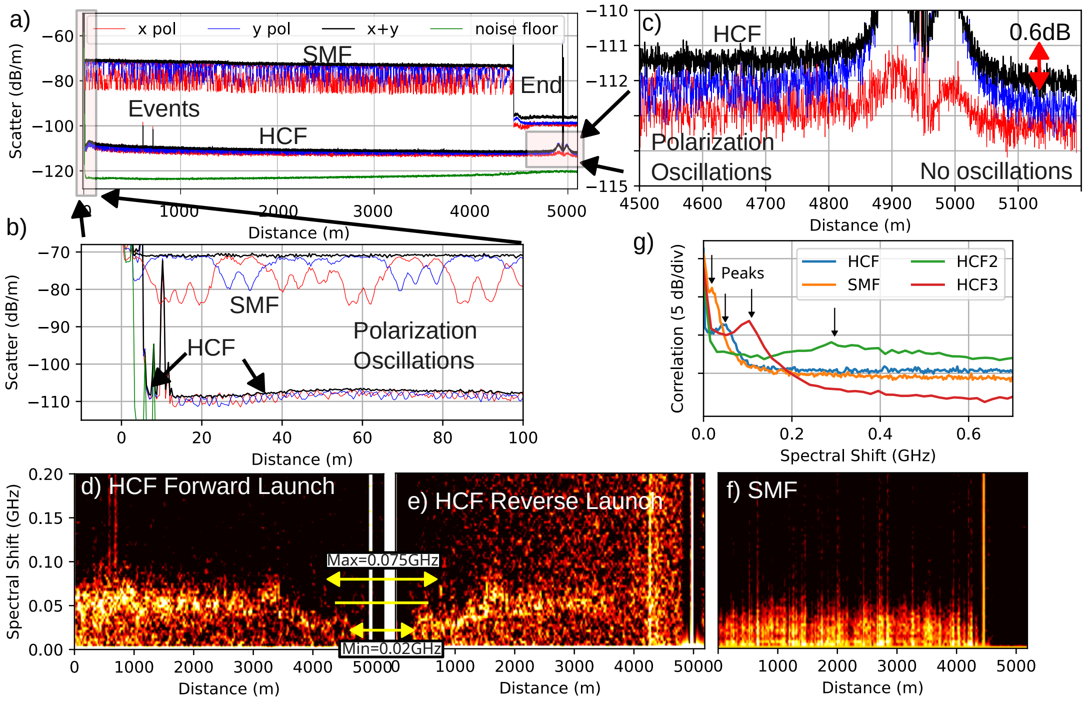

Fig. 2. Polarization resolved OFDR measurements of 4.9km DNANF. a) SMF,HCF and electronic noise floor. Zoom of the b) fiber launch and c) HCF end. Spectral shift between polarizations obtained via backscatter correlations for a HCF d) forward and e) reverse launch and f) SMF reference. g) Comparison of average polarization spectral shift of multiple fibers.

the backscatter. We find that the distributed phase thermal sensitivity of the mode ($d\beta L/dT$) is 20× lower than SMFs and measure the local birefringence between 5 and 16-m beat length along a 5-km long DNANF sample with sub mm resolution. Finally, we modify our OFDR technique to measure the sidewall scatter in links up to 100-km with meter-scale resolution, a demonstration that could find application in the deployment and monitoring of metro-scale HCF networks.

2. Thermal Sensitivity of HCFs using Distributed Spectral Shifts of Backscattered Speckle

Fig. 1a) shows the setup for the high-resolution OFDR comprising a continuously swept laser and a polarization diversified heterodyne receiver. The laser is split into a local oscillator (LO) path and a signal path that is directed into the HCF via a circulator and low back-reflection SMF pigtail. The two received polarizations are interfered with the LO and digitized at 400 MS/s. Not shown is a laser phase noise and sweep nonlinearity tracking asymmetric MZI with 1000 ns path length difference [6]. Standard OFDR post-processing is used with phase correction to obtain sharp traces after 5 km of HCF [7]. Scans of approximately 100 millon data points are taken over 800 GHz of bandwidth at 1550 nm which provides 184 μm Fourier transform limited resolution. This is an order of magnitude improvement over previous demonstrations of meter level resolution HCF OFDR [8].

Fig. 1c) shows a measurement investigating a 600-m piece of HCF with 2-m zoom in Fig. 1d). Both polarizations are shown as red and blue curves with the sum shown as a black curve (intentionally offset). The backscatter level is around -115 dB/m (about 40dB below SMF) and fluctuates up or down by 1 dB which we attribute to changes in the scattering coefficient due to varying fiber cross section. The apparent noisiness of the traces is the real side-wall scatter and is repeatable and complex valued. In SMF backscatter it is referred to as the ”Rayleigh fingerprint” and in HCF it is from the coherent superposition of frozen-in static side-wall scatterers.

Spectral correlations of this fingerprint measured between room temperature as the spool is heated reveals the thermal sensitivity of the modal phase to temperature (dβL/dT). Intuitively, as the fiber is heated, the scatterers appear further apart, shifting the reflected spectrum of each section to shorter wavelengths. In HCF, dβL/dT is dominated by length changes from the thermal expansion coefficient of fused silica (3 - 5$\times 10^{-7}$) whereas in SMFs, it is driven by the 20× stronger thermo-optic coefficient of silica. Fig. 1e) shows measured spectral shifts of HCF vs SMF as both were heated by 50°C and a linear fit with its slope showing 22× weaker HCF spectral shift. The shifts were calculated from the 1-m pigtail of SMF connected to the HCF and from the first 10-m of HCF.

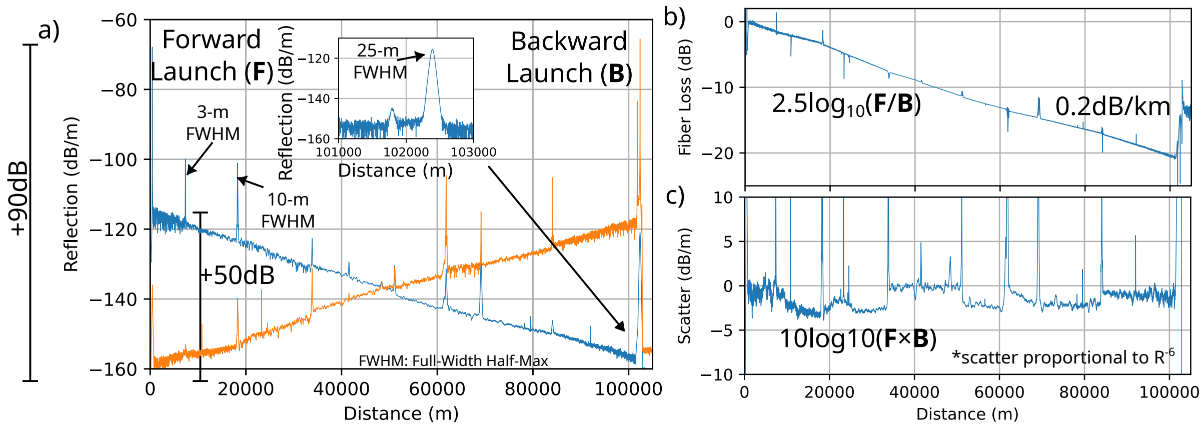

Fig. 3. Measurements of 100 km span averaged over 50 wavelengths with a) forward and backwards launches. Calculated b) fiber loss and c) scatter coefficient from the two measurements.

3. Distributed Modal Birefringence in 5-km HCFs

Fig. 2a) shows scans of a 5-km DNANF overlayed with those of a SMF with Rayleigh backscatter level around -72 dB/m. For both fibers, the rotation of the polarization state upon propagation shows as oscillations in power received in the x and y polarization respectively (red and blue), yet the total power remains constant. Fig. 2b) zooms into the first 100 m of the fiber to prominently show the polarization oscillations; this HCF sample quantitatively appears to have faster and more regular oscillations compared to SMF, indicating its shorter beat length. Fig. 2c) zooms in on a few hundred meters at the end of the fiber. Although the SNR is weaker, we can still observe the polarization oscillations before the end of the fiber and see an approximately 0.6dB difference between the fiber's backscatter and measurement floor (caused by the phase noise from the strong reflection).

From these traces, we evaluate the distributed birefringence ($\Delta\beta$) between the near-degenerate fundamental modes of this fiber via spectral cross correlation that will detect scatter replicas that are spectrally shifted by $\Delta\beta/\beta_0 f_0$. Figs 2(d,e) show the cross correlations between the two received polarizations in the forward and backward directions. 40-meter sections of fibers were used for the correlation to probe the small $\Delta\beta$. The backwards measurement of $\Delta\beta$ mirrors the forwards measurement and the peak of the spectral shift averages 0.05 GHz indicating a beat length of 8 m but varies between 0.025 GHz and 0.07 GHz. A functional verification of this methodology with SMF shows the expected single correlation peak. Finally, measurements of the spectral shift of a few different DNANFS (Fig.2g)) illustrate usefulness in non-invasive distributed fabrication quality control.

4. Long Range OFDR

The long range OFDR setup improves the sweep nonlinearity via external modulation using a dual pol IQ modulator and lowers the phase noise with a Hz-linewidth laser. X and Y polarization are swept over 250-MHz in 67-ms in opposite directions centered at 1-GHz offset frequency and theoretical 0.3-m Nyquist resolution. The full system is described in [9].

The launch signal is amplified to 10 dBm and the laser is stepped over 50 wavelengths with 1 GHz stepsize to average the coherent speckle to make smooth backscatter traces. No time gating was performed to block the strong signals from the SMF and SMF-HCF connection which can swamp most OFDRs. Fig. 3a) shows forward (F) and backwards (B) measurements of a 100-km span. From both measurements, the local scatter coefficient (F×B) that relates to local fiber structure and the fiber attenuation (F/B) can be separated and are shown in Fig. 3b,c).

In conclusion, we have adapted two novel OFDRs and used them to perform highly detailed distributed characterization of hollow-core DNANFs for the first time. Our techniques unlock ways to further improvements in fabrication, as well as line monitoring in 100-km scale links.

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