Characterisation of a Coupled-Core Fiber Using Dual-Comb Swept-Wavelength Interferometry

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Abstract *We present a measurement of the transfer matrix of a coupled three-core fiber using a novel combination of swept-wavelength interferometry and dual-comb spectroscopy capable of measuring 1 THz bandwidth with a frequency resolution of 50 kHz with only a 25 GHz laser sweep.*

Introduction

Application of space-division multiplexing (SDM) components in communication systems face different challenges such as overcoming limitations and distortions of the signal due to crosstalk, differential group delay, differential mode group delay (DMGD), etc., that become even more significant when the fiber cores are strongly coupled and the fiber is unstable. In order to obtain information about these effects and ways to mitigate them, it is essential to characterize the fiber's transfer function using fast and accurate measurement techniques.

Swept wavelength interferometry (SWI)[1] and dual-comb spectroscopy (DCS)[2],[3] are two widespread methods for characterization of devices in fiber optic and other photonic applications. Alongside with them, digital holography can be used for characterization SDM systems[4]. In SWI, a frequency sweeping source is used so the approach is beneficial to achieve high signal-to-noise ratio (SNR). However, broadband measurements require long sweeps during which the device under test (DUT) must be stable. Furthermore, deviations from a purely linear frequency sweep lead to significant measurement errors which require an additional reference interferometer for monitoring and compensation[5]–[7]. DCS is based on two frequency combs with a small difference in spacing and provides accurate measurements of phase and amplitude transfer functions. However, the discrete nature of the frequency combs implies that spectral information that falls between the comb lines cannot be detected and the spectral sampling resolution is limited. It has been demonstrated by our group that by combining SWI and DSC it is possible to obtain phase and amplitude with high resolution and speed[8]. In addition one can compensate the laser's sweep nonlinearity without any external reference interferometer. Such a system keeps the comb spacing constant and employs the laser sweep to simultaneously measure the intermediate frequencies over the full optical bandwidth, set by the width of the combs.

In this work we present a measurement of a three coupled-core fiber's (3CCF) transfer function using dual-comb swept wavelength interferometry (DC-SWI). Sweeping a tunable laser over the 25.15 GHz comb spacing enables fast (5 ms) and high-precision measurements over a bandwidth of 1.13 THz. The nonlinearity of the laser sweep can be compensated without an external reference interferometer using the averaged nonlinear phase component extracted from all comb line scans. The technique enables to measure group delays up to 20 μs with a resolution of 0.87 ps in a single sweep and characterise a transfer function with high frequency resolution of 50 kHz. Moreover, unlike SWI, our technique allows to capture short but broadband events, as the measurement is distributed over many wavelength. This opens the opportunity for new characterisation of dynamic effects in SDM fibers.

Experimental setup

The DUT is a 1.6 km 3CCF. The fiber cores are 9.5 μm in diameter and are made from pure silica. The distance between the cores is 22.5 μm. The cladding is fabricated from fluorine-doped silica glass with a standard diameter of 125 μm. The

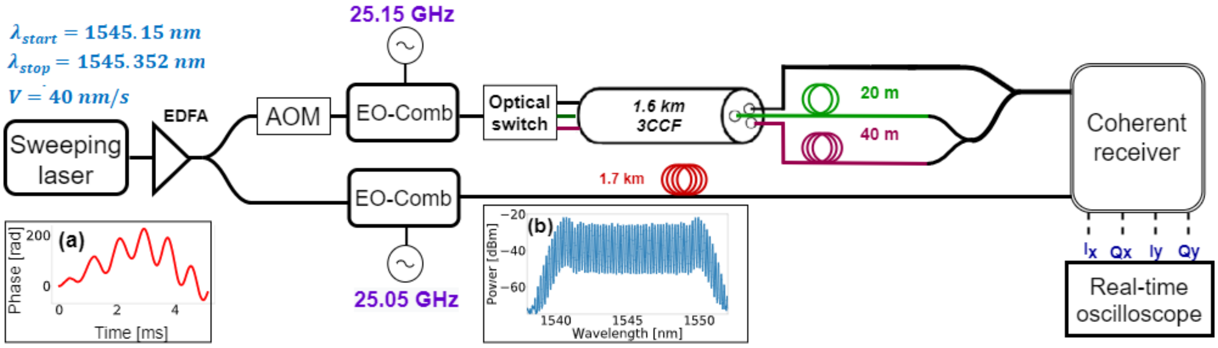

Fig. 1: Experimental setup. EDFA - erbium doped fiber amplifier, AOM - acousto-optic modulator, EO-comb - electro-optic frequency comb. Insets: (a) Recovered common phase from all comb lines showing the nonlinear laser sweep; (b) Optical spectrum of the frequency comb.

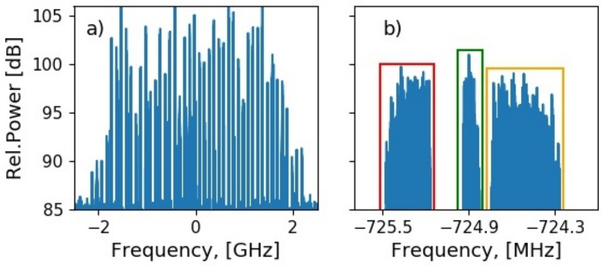

Fig. 2: a) Fourier transform of the raw measured electrical signal displaying the 100 MHz-spaced RF comb; b) Zoomed in image of the 16^{th} comb line showing 3 separate responses corresponding to output cores of the 3CCF.

core-cladding index difference, Δ, is 0.44% and the mode field diameter is 9.9 μm at 1550 nm. In order to couple the light into the different cores of the 3CCF and handle outputs from multiple cores, we used the fan-in/out devices that are based on ultrafast laser-inscribed 3D waveguides in a boro-aluminosilicate glass[9].

The experimental setup is shown in Fig. 1. Two electro-optic frequency combs with 25.05 and 25.15 GHz line spacing, and 45 lines each were used. The combs were seeded by a sweeping laser that swept 25.36 GHz bandwidth during 5 ms. It is important to operate with a sweeping bandwidth slightly larger than the frequency comb spacing in order to have an overlap between the comb lines so the transfer functions from neighboring lines can be coherently stitched[10]. A 25 MHz acousto-optic modulator was introduced for shifting away from DC the downconverted center line of the comb[2]. One of the combs went through the 3CCF, and the other comb was used as a local oscillator. An additional 1.7 km of single-mode fiber was added to the local oscillator arm for the purpose of making the delay difference between the arms similar. This is necessary in order to limit distortions coming from laser's sweep nonlinearity. We used an optical switch to change the input cores of the 3CCF during the measurement. Delay fibers of 20 and 40 m at the output of the 3CCF were included in order to separate impulse responses of different cores in the time domain. The length of these delays was chosen to be larger than the impulse response of a single core of the 3CCF. All 3 outputs of the 3CCF were then combined using 3-dB couplers and sent to a coherent receiver where it was sampled at 6.25 GS/s by a real-time oscilloscope. The scope sampling clock was locked to the 100 MHz beat-signal from the comb clocks[2]. Finally, all 9 elements of the transfer matrix were obtained using separate measurements for each input core. In future implementations input core delays can be added to enable a single-shot measurement of all inputs and outputs, but that was not used in this first demonstration.

Signal processing

In SWI, the laser's sweep nonlinearity can be a significant problem because it degrades measurements and needs to be compensated using an external interferometer. Therefore, it is favourable that in the DC-SWI experiment, this nonlinearity can be easily extracted and compensated using the nonlinear component of the common phase which is obtained by averaging the phase from all 45 comb lines[8]. This has two key advantages: first, it is not necessary to use an additional interferometer and second, in our experience measurement precision increases when using phase components from all 45 comb lines for processing.

The time-shifted responses of 3 cores at the 45 comb line wavelengths were extracted from the raw data by selecting appropriate windows around the responses in the time-domain (Fourier-transform of the raw measured signal from the oscilloscope) in every scan. Further processing was done on the separate segments that corresponded to every 3CCFs output core (fig. 2). First, phases of every windowed frequency range were calculated. Second, the linear part (i.e. the sweep) was removed in every phase. The remaining phase components were averaged over all lines to extract

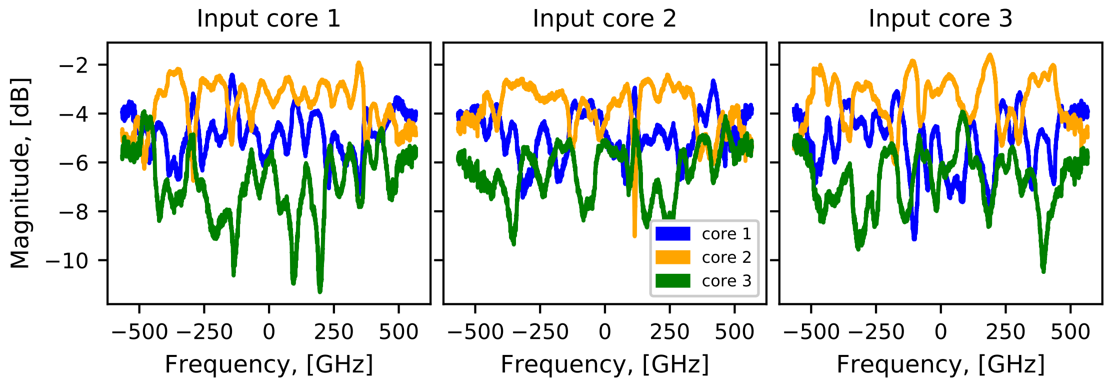

Fig. 3: Stitched magnitudes of the transfer function extracted from 45 comb lines with light entering the different cores

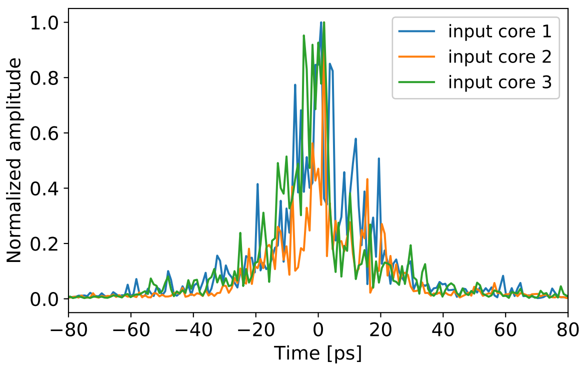

Fig. 4: Total power impulse responses of a 1.6 km 3CCF.

the common phase between lines. This common phase corresponds to the nonlinearity of the laser sweep, and is shown on inset (a) in Fig. 1, since it is the same for all the comb lines, whereas phase responses of the DUT depend on wavelength and are different in every window. All 45 scans were then compensated for the laser's sweep nonlinearity by subtraction of the common phase from the complex signal. Finally, the amplitudes and phases were stitched over the overlap regions to produce the broadband transfer function. Stitching of the amplitudes was carried out by averaging them in the overlap parts and then moving in respect to each other by a level difference.

Experimental results

Fig. 3 shows 3 traces with of the magnitude of the 3CCFs transfer function over the 1.1 THz comb bandwidth. The presented data is calculated as a sum of magnitudes of the respective X- and Y-polarizations and normalized by the total power from all cores. Each plot corresponds to a different input fiber core. For all inputs, around 10 dB variations in maximum/minimum transmission can be seen. Note that core 2 seems to have slightly higher power (1-2 dB on average in these measurements) than the other cores, which is likely due to different losses in the fan in/out connectors. The measurements are reproducible, in that a second measurement performed a minute later gives very similar spectra.

Fig. 4 demonstrates the total power impulse responses for each 3CCF's input core calculated as a sum of impulse responses corresponding to output cores. Every impulse response was normalized by its maximum value. It is apparent that curves show noisy behavior. A possible reason for the observed fluctuations can be reflections from fan in/out connectors. Discrepancies in a phase stitching process can also contribute to the imperfection of the responses' shape. The RMS widths of the impulse responses were estimated to be $T_{RMS_1} = 18.9$ ps, $T_{RMS_2} = 18.6$ ps and $T_{RMS_3} = 18.5$ ps. Using these values, DMGD of every fiber core can be calculated as $DMGD_i = T_{RMS_i}/\sqrt{L}$, where L is a fiber length and i is a fiber core number. Corresponding DMGDs are DMGD$_1 = 14.94$ ps/$\sqrt{\mathrm{km}}$, DMGD$_2 = 14.65$ ps/$\sqrt{\mathrm{km}}$ and DMGD$_3 = 14.62$ ps/$\sqrt{\mathrm{km}}$. These results are in a good agreement with properties of the coupled-core fibers that were published earlier[11]. The calculations are consistent with previously reported values for the 3CCF[12] and other coupled-core fibers[13].

Conclusions

We measured the 3CCFs transfer function combining SWI and DCS techniques. Using broadband frequency combs and sweeping over the all comb lines, fast and accurate full-field characterization measurements can be performed without any external interferometer.

Acknowledgements

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