Wideband Impulse Response Measurement of Coupled 2-Core Fibers of Various Lengths employing Dual-Comb Coherent Sampling

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Abstract: Transmission length dependency of complex impulse responses of coupled 2-core fibers are investigated using coherent sampling with picosecond time resolution over 20-nm bandwidth. Spectrally decomposed analysis is accomplished to observe the statistical nature.

1. Introduction

Space-division multiplexing (SDM) is a major topic of interest in optical fiber communications since it is a powerful scheme to boost the information-carrying capacity of optical fibers. Among various fibers have been developed for SDM transmission, coupled multicore fibers (C-MCFs) have been selected as the promising transmission channel due to their reduced group delay spread [1-3]. This attractive property is realized by random transition within the spatial modes of such fibers. Statistical analysis on C-MCFs over a broadband is an approach to understand the performance of suppression of the delay spread. For a statistical understanding of the group delay spread *i.e.* spatial mode dispersion (SMD), it is useful to measure it over a wide bandwidth, in which, the measured value at a particular sub-band could provide an instance of the entire measurement. It is also important to investigate the dependence of the group delay spread on the optical fiber length.

In this paper, broadband measurement of IRs of coupled 2-core fibers is performed using dual-comb coherent sampling, with sub-ps time resolution or over 20-nm bandwidth. We prepare two kinds of C-MCFs: one is a homogeneous core fiber and the other is a heterogeneous core fiber, both of which have the same core pitch. Several lengths of samples from 100 to 1000 m are arranged for each specification. Unlike broadband measurements based on swept-wavelength interferometers [4], balanced reference path is not necessary in such coherent sampling scheme, thereafter our system expedites measurement of fibers having different lengths. This property is especially advantageous when measuring optical fibers connecting two distant points. Finally, dependency of the SMD on the optical wavelength is investigated by spectrally-decomposed analysis.

2. Experimental setup and results

The experimental setup (see Fig. 1) was similar to the system that we have reported previously[5], except that the measurement bandwidth was expanded up to 20 nm (previously, a few nm) by broadening the spectra of the probe and the sampling comb using highly-nonlinear fibers (HNLFs). Two passive mode-locked lasers (frequency combs) yield the probe and sampling pulses. The repetition frequencies of the probe and the sampling comb are f_p=20 MHz and f_s=10 MHz, respectively. The small detuning of the repetition frequencies Δf was introduced by manual control on cavity temperature, so that the equivalent sampling interval to be set at ~0.2 ps. The pulses were nearly transform-limited with spectral width of a few nm. The pulses were incident on such HNLFs with normal chromatic dispersion, and consequently the spectra were expanded to several tens of nm. To avoid aliasing noise, programmable optical filters (InLC Technologies) were used for extraction of approximately 20-nm (2.5 THz) wide chunk from the broadened spectra. With an appropriate numerical chromatic dispersion compensation, the probe and those sampling pulses yield temporal profiles of ~1 ps width, which determine time resolution of the IR measurement. An auxiliary interferometer monitored the beat signals between those combs and the single frequency CW laser, which is used for compensation of the relative phase fluctuation between the combs. The typical acquisition time of the IR was a few ms. Natural fluctuation of Δf during the acquisition period may cause time-scale errors, however, currently we believe that the effect of such errors is not significant in group delay analysis.

Specifications of the two kinds of C-MCFs prepared for the measurement are summarized in Tab. 1. The homogeneous type has two identical cores, whereas the heterogeneous type has two cores with slightly different diameters and different refractive indexes. Refractive index distributions of them have step-index profiles. The core distances are the same for both fibers. For each type of the fiber, we prepared samples of several different lengths (100, 200, 500, and 1000 m). Fan-in and fan-out (FIFO) were attached to those 1000-m long samples. As for other samples with different lengths, a single-mode fiber was fusion spliced into one core at both ends. The probe pulse was input to one of the cores of the fiber. For 1000-m long fiber, the output IRs were time interleaved in a single mode fiber with a relative delay of ~1 ns, so that the IRs of those two cores can be observed simultaneously. For other fibers, only the IR of one core was observed. The above-mentioned IRs were measured with polarization-diversity detection.

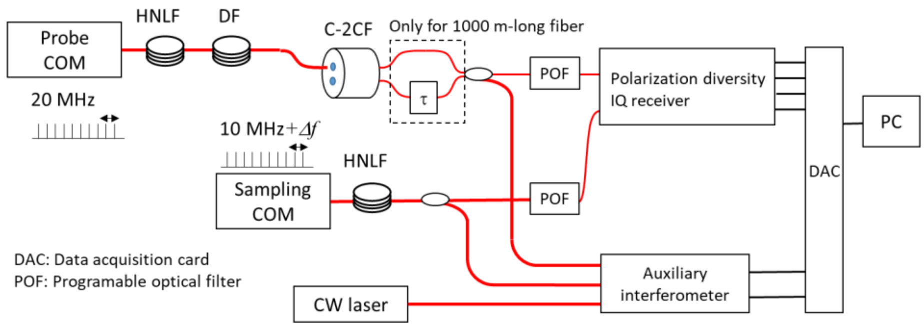

Fig. 1 Experimental setup. Dispersive fiber (DF) was used for providing initial chirp to prevent strong nonlinear effects in the fibers under measurement.

Table 1 C-2CF under measurement.

	Core diameter (Relative refractive index difference)		Inter-core distance	Clad diameter
	Core #1	Core #2		
Homogeneous	8.4 μm (0.37%)	8.4 μm (0.37%)	21.5 μm	125 μm
Heterogeneous	8.0 μm (0.38%)	9.0 μm (0.35%)	21.5 μm	125 μm

Figure 2 shows the power IRs observed at one output core with the entire bandwidth. In these results, numerical chromatic dispersion compensation was accomplished to obtain the minimum root mean square of the IR spread for each case. From Fig. 2, all the measured IRs involve random fluctuations, which can conceivably be hypothesized to be caused by random mode coupling in the optical fibers. The IR spreads are several times larger in heterogeneous fiber compared to those in homogeneous one. Discrepancy in IRs of different polarizations can be attributed to strong polarization dependency during transmission. Fig. 3 shows the corresponding power spectra of the IRs where random fluctuations can also be observed. Another interesting finding to emerge from Fig. 3 is that the correlation width of the spectrum decreases as the fiber length increases.

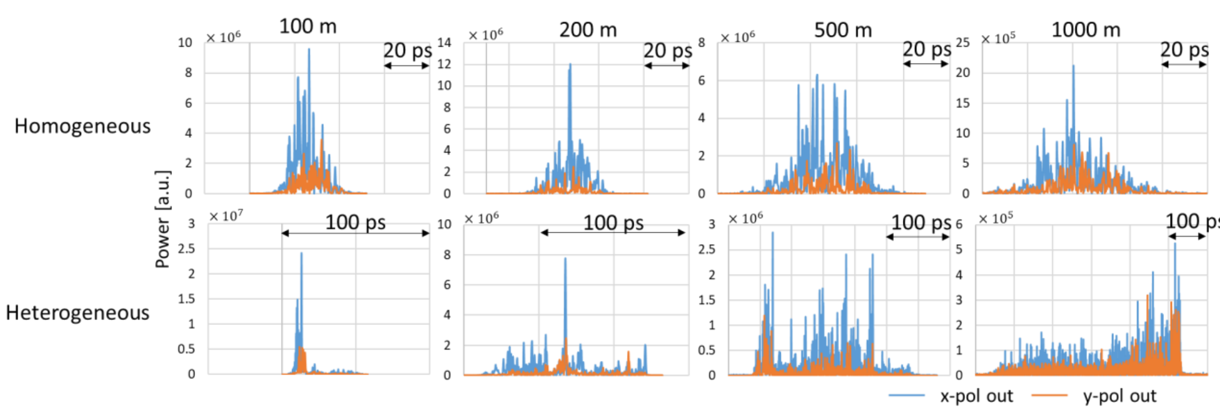

Fig. 2 IRs observed at one output core in homogeneous and heterogeneous 2CF.

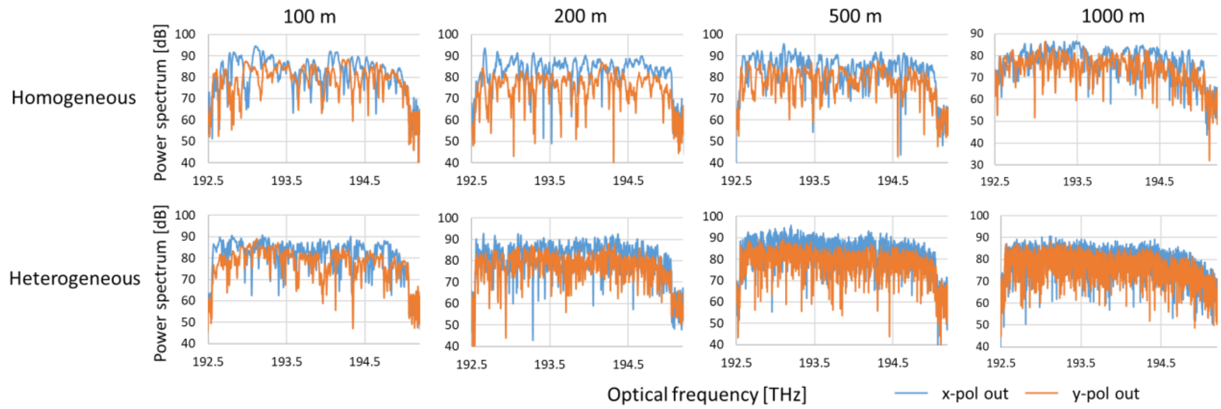

Fig. 3 Power spectra of the observed IRs.

The double root-mean squares of the measured IR or SMD which were estimated from the above full-bandwidth IRs are plotted in Fig. 4 with respect to the fiber length. For fiber A, the fitting proportional to the square root of the length matched well. In contrast, in fiber B, the spread varied almost linearly with length. The fitting curves added in the figure show 32 $ps/\sqrt{km}$ for the homogeneous fibers and 277 ps/km for the heterogeneous fibers, respectively. Next, spectrally-decomposed analysis of the IRs was accomplished. In Fig. 5, the blue and red plots show SMDs calculated with rectangular spectral windows having bandwidths of 50 GHz in the 1000-m long fiber. In this analysis, we used averaged power of four IRs (core #1 and core #2, and x-y polarizations output) because the power of a specific IR may be too small to conduct the SMD analysis when the spectral window is decreased to the above level. What is striking about the results shown in Fig. 5 is that SMDs have considerable fluctuations in the spectral domain, while their averages are close to the results of the full-bandwidth analysis.

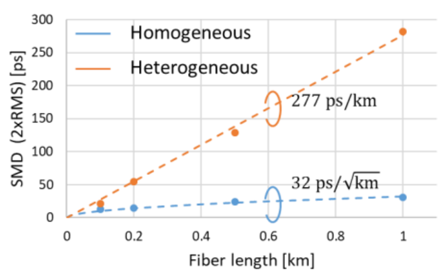

Fig. 4 Measured full bandwidth SMDs

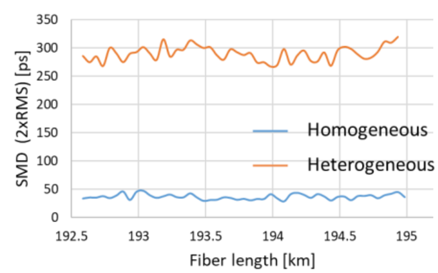

Fig. 5 Measured SMD spectrum in 1000-m long C-2CF obtained with a 50-GHz window

3. Summary

Broadband and spectrally-decomposed analysis of SMD was performed in coupled 2-core fibers of various lengths, based on dual-comb coherent sampling. The system setup is quite simple: a pair of free-running frequency combs were used for probe and local oscillators, and natural fluctuation of repetition frequency detuning was neither controlled nor compensated during the measurement time to obtain a single IR. The measurement range of the delay is limited by the repetition frequency (currently up to 50ns). With the current C-MCFs and bandwidth settings, the dominant factor in IR spread is chromatic dispersion, and in this context, the measurement range can accommodate fiber lengths of ~100 km. With its broadband nature and adoptability for length variation, the presented method would be useful for characterizing SMD's in C-MCFs.

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