Stable Measurement of Effective Area in Coupled Multi-core Fiber

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Abstract: We achieved stable near-field and far-field patterns measurements and effective area evaluation of randomly coupled multi-core fibers by using a wide-bandwidth light source to average intensity over wavelength and eliminate time-varying intensity fluctuations.
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1. Introduction

The transmission capacity of single-mode fiber (SMF) is bounded theoretically by the nonlinear Shannon limit [1]. Current research is starting to approach this limit, and further improvements to SMF system parameters such as amplifier noise figure, channel spacing, fiber loss, and nonlinearity coefficient will only marginally increase the maximum achievable capacity [2]. To continue the exponential growth of communication systems, space-division multiplexing (SDM) with new fiber designs should be considered [3]. Among various SDM fibers, randomly coupled multi-core fiber (RC-MCF) with pure silica cores offer higher channel density than uncoupled MCF while avoiding the high loss of Ge-doped few-mode fiber (FMF). Previous theoretical and experimental studies have shown that strong random mode coupling can suppress differential group delay (DGD), mode-dependent loss, and nonlinearities [4,5]. These advantages make RC-MCF a suitable candidate for further investigation.

Many properties of RC-MCF, such as average attenuation, cutoff frequency, bend loss, spatial mode dispersion, and chromatic dispersion have well-established measurement methods [4]. Another important parameter for long-haul, high-capacity systems is the effective area (A_{eff}) of the fiber. In SMF, the nonlinear coefficient is inversely proportional to A_{eff}, and nonlinear performance of more complicated fiber types also depends on A_{eff}. Therefore, to estimate transmission performance, accurate values for A_{eff} are necessary. However, the random coupling in RC-MCF has made measurement of A_{eff} unstable and difficult.

In this paper, we present measurement methods for the core effective area ($A_{\mathrm{eff,core}}$), in RC-MCF with strong mode coupling. Using a wide-bandwidth light source in a several km-long fiber, successful measurements of the $A_{\mathrm{eff,core}}$ in RC-MCFs with three and four cores are achieved.

2. Incoherent NFP/FFP measurements for $A_{\mathrm{eff,core}}$ evaluation

The A_{eff} of an optical waveguide is defined using the near-field pattern (NFP), and A_{eff} of an SMF can be accurately measured using the far-field scanning (FFS) method [6]. In this method, the angular profile of the (circularly symmetric) far-field pattern (FFP) is measured, the FFP profile is numerically converted to a radial NFP profile using the Hankel transform (HT), and A_{eff} is calculated from the NFP. Alternatively, the NFP can be measured directly, but the magnifying optics required act as a low-pass filter. Consequently, the measured NFP and thus A_{eff} may not be accurate given the small spot size of optical fibers. Typically, the field profile of an SMF is measured using a short fiber sample and a narrow-linewidth light source; however, when we observe the field profiles of an RC-MCF in this way, the field profile fluctuates due to time-varying random mode coupling.

To mitigate these intensity profile fluctuations, which are caused by optical interference, we use a long fiber sample and a broadband light source for field profile measurements of RC-MCFs. The output light from each mode of an RC-MCF is the sum of light that has traversed various optical paths with different phase delays due to random coupling along the fiber, and the phase differences accumulated over these paths vary with time and wavelength of light; thus, the intensity of each mode also varies due to interference. However, the output intensity of a long RC-MCF averaged over a sufficiently broad wavelength range is stable, and the power is distributed equally in each mode. This can be understood as reducing the degree of coherence by increasing the linewidth of the light source and/or by increasing the optical path length difference between the interfering light components. So by simply using a long RC-MCF sample and a broadband light source, a stable NFP/FFP can be observed.

An interesting finding from these incoherent measurements is that the FFP of the RC-MCF approximately equals the average FFP of all cores of the RC-MCF, which can be explained with Fig. 1 as follows. The NFP is converted to its corresponding FFP through Fraunhofer diffraction, and the NFP-FFP relationship is expressed as the two-dimensional (2D) Fourier transform (FT). Therefore, core position (or NFP center) displacement from the fiber center

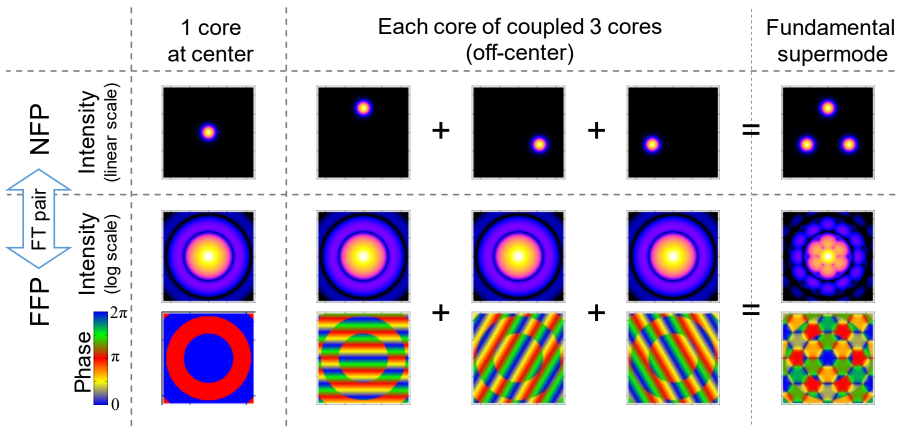

Fig. 1. The relationship between the NFPs and FFPs of a single core and of coupled cores.

tilts the FFP equiphase plane, but does not affect the absolute value of the FFP amplitude, as shown in the center column of Fig. 1. Since the FT is a linear operation, when we consider superposition of the core modes with common phase, its FFP is the superposition of the core mode FFPs, as shown in the right column of Fig. 1. Interference between the core modes modulates the intensity of the FFP of the superposition, and the intensity envelope is proportional to the FFP of a core mode. Thus, an RC-MCF exhibits a complicated FFP in coherent measurement. In our incoherent method, since a low-coherence broadband light source is used, the average over random phases eliminates the modulation and only the envelope remains, i.e., the average FFP of all cores of the RC-MCF is observed. Therefore, the measured FFP and recovered NFP retain circular symmetry, implying that the far-field scan technique is applicable to RC-MCF. In order to validate the measurement method, we also record 2D data of the FFP using an infrared camera, even though it suffers from reduced dynamic range.

Using the method described above, 2D NFPs and FFPs were measured for three- and four-core RC-MCFs (3CF and 4CF [4]). The fiber properties are shown in Table 1 (measurement results will be discussed later). A superluminescent diode (SLD) with a center wavelength of 1558 nm and a 3-dB bandwidth of ~4.76 THz was used as the light source. Light from the SLD was launched into a single core of an RC-MCF, and the fiber lengths were sufficient for inducing complete power mixing over all cores, with sufficient modal dispersion (MD) to suppress the coherence. Figure 2 shows the NFPs directly observed using a magnifying optic and infrared camera, and the FFPs observed using an *f*-theta lens and infrared camera, all of which were quite stable. As expected, we see no interference fringes in the measured FFP. The measured NFP and FFP profiles were compared with reference profiles calculated from core preform rods using a finite-element method (FEM) at 1550 nm, as shown in Fig. 3. The direct measurement results are in good agreement with the FEM-calculated profiles, except for errors resulting from the limited dynamic range of the cameras. The limited dynamic range decreases the accuracy of the NFP numerically converted from the measured FFP, as can be seen in Fig. 3b. To confirm the circular symmetry, the measured FFPs were converted to NFPs both by 2D FT and 1D HT. The two resulting NFP profiles are in good agreement. For 4CF, there is a noticeable

Table 1. Design parameters and measured properties of RC-MCF

Sample	Design				Measurements					Wavelength averaging error of $A_{\mathrm{eff,core}}$ meas.
	# of cores	Core pitch (μm)	Core MFD*1 (μm)	$A_{\mathrm{eff,core}}$*1 (μm^2)	Length (km)	SMD*2 (ps)	$A_{\mathrm{eff,core}}$ (μm^2) NFP*3	FFP*4 (2D FT)	FFP*5 (1D HT)	
3CF	3	22.5	9.6	78	7.2	13.8	78.1	80.0	77.3	0.58 μm^2 (0.74%)
4CF [4]	4	20	11.4	112	3.0	12.0	115.9	115	111	0.62 μm^2 (0.62%)

*1: Calculated from core preform rods using FEM at 1550 nm. *2: Values measured from 1520 to 1580 nm. *3,4,5: NFP was obtained by (*3) direct NFP measurement, (*4) 2D inverse Fourier transform of a measured FFP, or (*5) inverse Hankel transform of a measured FFP.

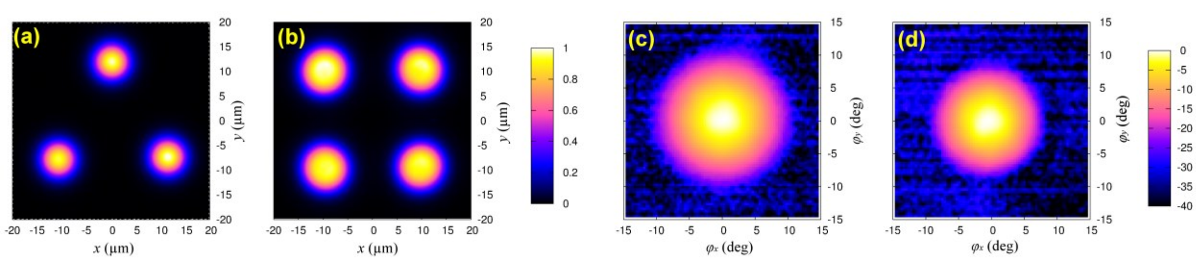

Fig. 2. Two-dimensional (a,b) NFP intensity (linear scale) and (c,d) FFP intensity (decibel scale) images of (a,c) 3CF and (b,d) 4CF.

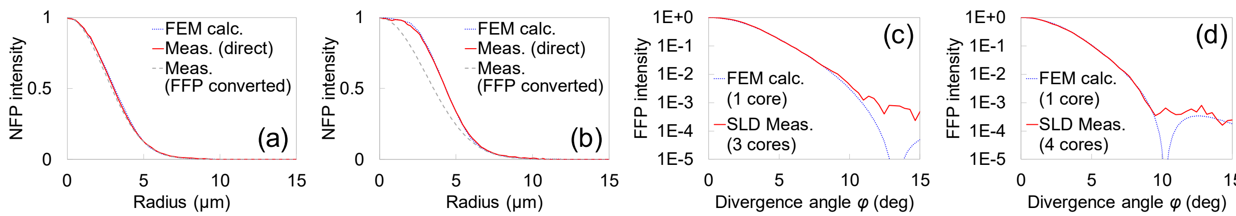

Fig. 3. (a,b) Radial NFP profiles and (c,d) angular FFP profiles of (a,c) 3CF and (b,d) 4CF.

error in the NFP calculated from the FFP, as seen in Fig. 3b. We suspect this is because the high-spatial-frequency (large-angle) components of the FFP cannot be measured owing to the noise floor of the FFP camera (we replaced noisy values by zeros). From these measurement results, $A_{\mathrm{eff,core}}$ of the RC-MCFs were obtained, as shown in Table 1. For measured NFP $A_{\mathrm{eff,core}}$, the means and standard deviations across all cores are listed.

The $A_{\mathrm{eff,core}}$ depends on the NFP, so it inherits the wavelength dependence of the NFP. Thus, it is expected that using a broadband light source, while essential for stability, also introduces error in the $A_{\mathrm{eff,core}}$ measurement. The SLD's wide bandwidth weights the measured intensity by its power spectrum, slightly changing the shape of the NFP and influencing $A_{\mathrm{eff,core}}$ calculation. However, numerical analysis confirmed that this averaging of NFP intensity over the SLD power spectrum should account for <1% error in $A_{\mathrm{eff,core}}$, as shown in Table 1.

3. Analysis of nonlinearity and $A_{\mathrm{eff,core}}$

In analyzing nonlinearity in many fiber types, two basic assumptions are weak guidance and negligible mode-dependent loss. For SDM fibers, the added assumption of strong coupling among modes enables the coupled nonlinear Schrodinger equations to reduce to the simpler coupled Manakov equations. In RC-MCF with M cores, all modes are nearly degenerate, so there is only one mode group, in which all modes couple strongly. In the SMF Manakov equations, the nonlinear terms have a factor $(8/9)\gamma$, where $\gamma = (\omega_0 n_2/\mathrm{c})/A_{\mathrm{eff}}$ is the nonlinearity coefficient. Antonelli *et al.* [7] prove that for RC-MCF satisfying the above assumptions and ignoring MD, the factor $(8/9)\gamma$ from the SMF case is replaced by $\gamma\kappa = (4/3)[(2M)/(2M+1)]\,\overline{\gamma}$ in the coupled propagation equations, where $\overline{\gamma}$ is the multimode equivalent of γ with A_{eff} replaced by the average (harmonic mean) effective area over all mode pair combinations.

Under the supermode model of coupled MCF, eigenmodes are linear combinations of the core modes [8], so for evaluating average effective area, any normalized mode basis is valid. A convenient basis is the core basis. If overlap between core fields is small, the average effective area of the supermodes is simply $MA_{\mathrm{eff,core}}$, so $\overline{\gamma} = (\omega_0 n_2/\mathrm{c})/(MA_{\mathrm{eff,core}})$. This effective area increase reflects the property in RC-MCF that modes are not isolated to one core, but are distributed among all cores. Small core overlap is desirable in RC-MCF for uncoupled supermodes to remain nearly degenerate so group delay spread is small. Larger core overlap will decrease effective area, increasing nonlinearity. In our fibers, the 3CF has no observable overlap, and the 4CF has slight overlap, but this only decreases the average effective area from 4 $A_{\mathrm{eff,core}}$ to about 3.9996 $A_{\mathrm{eff,core}}$. As M increases, average effective area scales linearly in M.

Antonelli *et al.* [7] also show that accounting for slightly different propagation constants of each mode further reduces nonlinearity by a factor $(2M+1)/(4M)$, because MD averages nonlinear interactions between modes. Two polarizations from M modes contribute to nonlinear noise, so nonlinear noise variance is proportional to $2M[\gamma\kappa(2M+1)/(4M)]^2 = (4/3)\gamma^2/M$.

4. Conclusion

The measurement of a km-scale RC-MCF using a broadband SLD as light source achieves stability in NFP intensity imaging by averaging intensity fluctuations from interference between cores across wavelength and phase delay. Such measurements can be used to calculate an average effective area of the core modes from their phase-averaged NFP. The core effective area can be used in determining the nonlinear coefficient of the fiber, which governs transmission capacity. Contributions to the FFP from each core combine in a way that retains circular symmetry, so the accuracy of $A_{\mathrm{eff,core}}$ measurement can be increased by using the far-field scanning technique to obtain FFP angular profile data that achieves both high dynamic range and high spatial resolution.

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