Characterization of Coupled Multi-core Fiber Nonlinearity using Modified CW-SPM Method

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Abstract: Narrow bandwidth continuous-wave-based SPM method is proposed for measuring the effective nonlinear coefficient γ_{eff} of coupled multi-core fibers. We confirmed that the measured γ_{eff} with 2- or 4-core fibers agreed well with the theoretical model.

1. Introduction

A coupled multi-core fiber (MCF) is an attractive space division multiplexing (SDM) fiber for high capacity transmission since it has a much smaller core pitch and accommodates larger number of cores than those of uncoupled MCFs. The coupled MCF has unique properties owing to the random mode coupling in the MCF such as the narrow group delay spread specified by the spatial mode dispersion (SMD) coefficient in the ps/√km unit [1]. The lower nonlinearity of the coupled MCF has been experimentally confirmed in a 4-core transmission by comparing the single mode fiber (SMF) with the comparable fiber loss and effective area of the core mode [2]. Although the advantage of the nonlinear performance of the coupled MCF has theoretically been investigated [3, 4], a measurement method for the nonlinear property of the coupled MCF has not yet been investigated, which is mandatory for fabricated fiber characterization and transmission system design.

In this paper, we investigate the applicability of the continuous-wave (CW)-based self-phase modulation (SPM) method [5] by modifying the wavelength difference between two CW lights to more than 10 times smaller value to suppress the spectral fluctuation and pulse distortion induced by the mode coupling and dispersion. We also reveal that the modified CW-SPM method well characterizes an effective nonlinear coefficient [3] in a coupled MCF with various core numbers and coupling coefficients.

2. Theoretical treatment and measurement principle

The mode propagation in a coupled MCF is expressed by [3]

$$\frac{\partial \bar{\boldsymbol{A}}}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 \bar{\boldsymbol{A}}}{\partial t^2} = ik\gamma(|\bar{\boldsymbol{A}}|^2)\bar{\boldsymbol{A}} \qquad (1),$$

where $\bar{\boldsymbol{A}}$ is the slowly varying field envelope of the propagation mode, γ is the nonlinear coefficient, and k is the nonlinear reduction factor (definition is shown in Sec. 3). Here, higher-order chromatic dispersion and loss are ignored for simplicity. Although there are multiple modes in the coupled MCF, they are expressed as one mode in Eq. (1) with the averaged group delay, chromatic dispersion β_2, etc., among all propagation modes owing to the random mode coupling. The $|\bar{A}|^2$ is the total electric power of all modes. As the right term represents the well-known SPM effect, $k\gamma$ can be treated as the effective nonlinear coefficient γ_{eff} that characterizes the nonlinear performance of the coupled MCF. This equation also indicates that a similar methodology for the γ measurement of SMF using SPM can be applied for the coupled MCF when each field (propagating through each mode) has the same envelope field. The conventional CW-SPM method utilizes two CWs with the appropriate wavelength interval $\Delta\lambda$. The two CWs are multiplexed with same linear polarization state, and input into the fiber under test (FUT). The $\Delta\lambda$ is determined taking into account the total dispersion of the FUT since the propagating field envelope should not be distorted, and typically the $\Delta\lambda$ and FUT lengths are set to about 0.3 nm and 500 m, respectively [5].

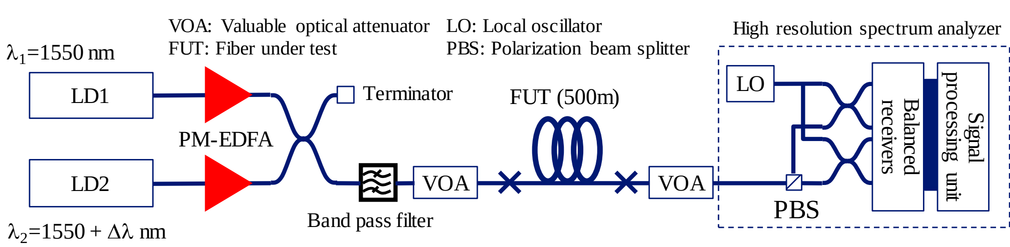

Fig. 1 Measurement setup for effective nonlinear coefficient of coupled MCF

There are two important considerations when applying the CW-SPM method to the coupled MCF. One is the spectral fluctuation owing to the unstable mode coupling in the MCF. The nonlinear phase shift in the propagating sinusoidal pulse can be derived from the spectral power ratio between the main and sub peak (I_1 / I_2). However, the core-to-core insertion loss has a strong spectral dependency owing to the modal dispersion, and the spectrum can be asymmetric with the conventional condition. The other consideration is the pulse distortion by the modal dispersion. Typically, coupled MCF has tens ps/√km modal dispersion, which has more impact on the pulse distortion than the chromatic dispersion of tens of ps/nm/km. We here propose a modified CW-SPM method where the Δλ is reduced to a more than 10 times smaller value to suppress the spectral fluctuation and modal dispersion induced pulse distortion. The point of this technique is based on the fact that the peak ratio is derived from the nonlinear phase shift ϕ_{max} as

$$I_1/I_2 = \{J_0^2(\phi_{max}/2) + J_1^2(\phi_{max}/2)\}/\{J_1^2(\phi_{max}/2) + J_2^2(\phi_{max}/2)\} \qquad (2),$$

and is thus theoretically independent of Δλ. Figure 1 shows the proposed setup for measuring the γ_{eff} of the coupled MCF. The input configuration is the same for the conventional CW-SPM method except for the Δλ setup. The Δλ value in the modified CW-SPM was too small to spectrally distinguish the measured peaks with the conventional optical spectrum analyzer (OSA). Here, the coherent and signal processing-based ultra-high wavelength resolution OSA (AP2071A, APEX technologies) with a spectral resolution of 0.8 pm was used in the experiment.

3. Results and discussion

Table 1 shows the structural parameters of the FUTs. The GeO_2 doped cores or Fluorine doped cladding coupled MCFs with 2 and 4 cores and 18~25 μm core pitch were used. Figures 2(a) and (b) show the example spectrum using a 500-m-long 2-core fiber (ID = 4) when Δλ is 0.28 nm and 0.01 nm, respectively. The bending radius of the FUT was 80 mm, and the OSA used for Figs. 2(a) and (b) was the conventional and coherent-based one, respectively. The input/output SMF was spliced with one of the cores of the MCF. The obtained spectrum was well symmetric and the peak ratio was stably measured by reducing the Δλ adequately. Figure 3 shows the Δλ dependence of I_1 / I_2 with the SMF and 2-core fiber. The plots show the averaged value of the acquired 20 spectra and the error bar shows the max./min. values. The I_1 / I_2 was independent of Δλ for the SMF measurement. However, the measured I_1 / I_2 value for the 2-core fiber was Δλ dependent, which was expected owing to the modal dispersion. We experimentally confirmed that the peak ratio became stable and almost Δλ independent by reducing the Δλ to below 0.05 nm. Although the maximum Δλ for the measurement differs depending on the total modal dispersion of each MCF, the fiber length or Δλ was set with a margin to 500 m or 0.01 nm, respectively, for all FUTs taking into account that all FUTs have comparable SMD coefficients as shown in Table 1. Figure 4 shows the nonlinear phase shift ϕ_{max} calculated from the measured I_1 / I_2 as a function of the total input power P_{in}. The plots are the averaged value among the 10

Table. 1 Structural parameters of FUTs

ID	# of cores	Core pitch Λ (μm)	Dopant	Core radius *a* (μm)	Relativ index difference Δ (%)	SMD coefficient (ps/√km)
1	1	NA	GeO_2 core	4.2	0.34	NA
2	2	20	GeO_2 core	4.5	0.44	31
3	2	25	GeO_2 core	4.5	0.40	43
4	2	20	F cladding	4.5	0.38	42
5	2	25	F cladding	4.4	0.35	41
6	2	21	F cladding	3.3	0.67	25
7	2	21	F cladding	4.8	0.30	30
8	4	18	F cladding	4.2	0.33	16

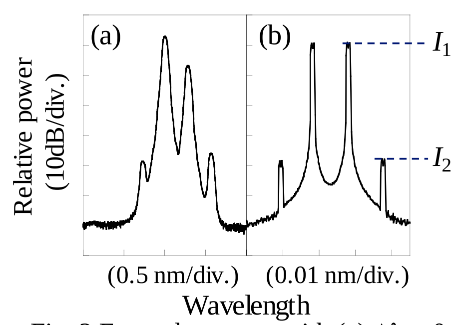

Fig. 2 Example spectra with (a) Δλ = 0.28 and (b) 0.01 nm

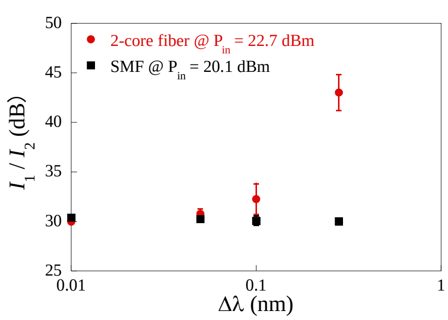

Fig. 3 Δλ dependence of I_1 /I_2

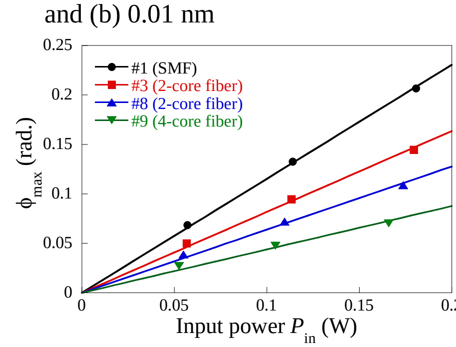

Fig. 4 Input power vs. nonlinear phase shift

times spectrum data. The results for SMF and coupled MCFs with ID = 3, 8 9 are shown as examples. The solid lines correspond to the fitted results. We observed well linearity between P_{in} and ϕ_{max} for each result. The nonlinear coefficient in $W^{-1}km^{-1}$ unit can be derived by $1/(2L_{eff})\, d\phi/dP_{in}$.

To analyze the validity of the measured values, the obtained values were compared with the calculated ones. The effective nonlinear coefficient γ_{eff} (=$k\gamma$ in Eq. (1)) is expressed by

$$\gamma_{eff} = k\gamma = \sum_{k\leq l}^{M} \frac{32}{2^{\delta_{kl}}} \frac{1}{6M(2M+1)} \frac{n_2 \varpi_0}{c A_{eff}^{kl}} \qquad (3)$$

where M is the number of cores, and A^{kl}_{eff} is the conventional (k=l) or inter-modal ($k\neq l$) effective area defined as the effective area of the fundamental mode divided by f_{kkll} (see [3] for a detailed definition). The fiber bending and twisting significantly affects the mode field in the coupled MCF. We calculated the rotation angle dependence on A^{kl}_{eff} and γ_{eff} values for the 2-core fiber with a bending radius of 80 mm. The A^{11}_{eff} and A^{12}_{eff} corresponds to the A_{eff} of the even mode and between the even and odd modes, respectively. The θ is defined as the rotation angle, where $\theta = 0$ indicates that the two cores are both in the line of the bending direction. While the A^{kl}_{eff} greatly changes in the vicinity of θ = 90° [1], it is found that the γ_{eff} value is almost insensitive for θ. This behavior can be roughly understood from the electrical fields. For θ = 0°, each mode propagates in different cores and A^{11}_{eff} and A^{22}_{eff} become almost A_{eff} of the core mode, and A^{12}_{eff} is large enough to ignore the inter-modal nonlinear effect. For θ = 90° in contrast, A^{11}_{eff} and A^{22}_{eff} has a twice larger A_{eff} of the core mode, and A^{12}_{eff} has a comparable value. In either case, the γ_{eff} value becomes the same by balancing the nonlinear contribution between A^{kk}_{eff} and A^{kl}_{eff}. The rotation direction insensitivity on γ_{eff} was also confirmed for the other FUT including the 4-core fiber. Thus, the probability distribution of the bending direction in the 500-m FUT does not affect the γ_{eff} measurement. We then calculated the γ_{eff} of each FUT and compared the measured and calculated γ_{eff} as shown in Fig. 5. The nonlinear index n_2 of the FUTs were estimated on the basis of the data in [6]. The fiber IDs are noted in the figure. Note that γ_{eff} indicated here does not mean how much the nonlinear effect is reduced from that for the SMF in the mode division multiplexed (MDM) transmission with MIMO processing. This is because the γ_{eff} value was characterized when the total input power to the FUT was the same on the basis of Eq. (1). This indicates that the input power per core in the MCF is M times smaller than that for the SMF. The obtained γ_{eff} is, however, an inevitable parameter for estimating the nonlinear impairment of the MDM transmission system by numerically solving Eq. (1) by taking into account the input signal pattern difference and modal dispersion induced nonlinear mitigation. The relationship between the measured and calculated γ_{eff} is well correlated and almost on the line of $y = x$, and thus the applicability of the proposed measurement method was proved.

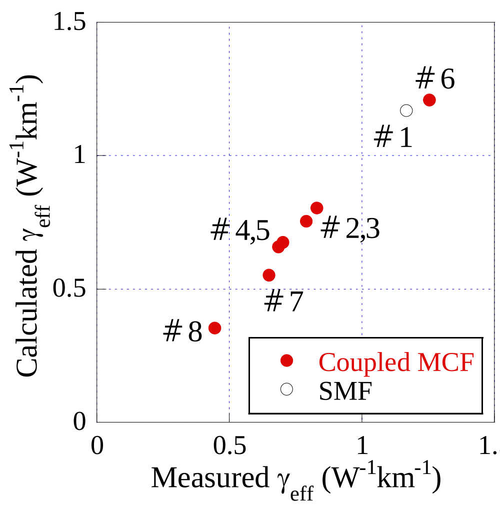

Fig. 5 Comparison of calculated and measured γ_{eff}

5. Conclusion

We proposed a modified CW-SPM method for measuring the effective nonlinear coefficient γ_{eff} of the coupled MCF, where the wavelength difference between two CWs was reduced to 0.01 nm to suppress the spectral and pulse distortion of the propagated light in the fiber. The measured γ_{eff} obtained with various coupled MCFs with 2~4 cores agreed well with the theoretical model.

References

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