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On the Degree of Polarization of the Intercore Crosstalk in Weakly-Coupled Multicore Fibers

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***Abstract*—The degree of polarization of the intercore crosstalk (ICXT) field induced by weakly-coupled multicore fibers is investigated by simulation. Systems with |skew|×bit-rate<<1 and employing low-linewidth lasers generate polarized ICXT. Instead, for systems with |skew|×bit-rate>>1 and |skew|×laser-linewidth>>1, the induced ICXT tends to be completely unpolarized.**

***Keywords*—Multicore fiber, weakly-coupled, intercore crosstalk, degree of polarization.**

I. INTRODUCTION

Weakly-coupled multicore fiber (WC-MCF) technology has shown high potential to be used in next generation optical networks as it can be easily upgraded for use in existing equipment and requires no complex signal processing based on multi-input multi-output [1]. In WC-MCFs, the non-negligible mode coupling between cores leads to the accumulation of intercore crosstalk (ICXT) between cores. MCFs with higher core count or shorter core-to-core distance suffer from higher ICXT power which may lead to significant system performance degradation [2].

The ICXT induced by WC-MCFs has been widely studied in the last years. It has been shown that the ICXT power is random and may vary along time and frequency [3,4]. The relevance of intra-core polarization dynamics in the accumulation of inter-core coupling along the fiber has been also analysed [5]. Further investigation showed that the relative polarization between signal and ICXT fields may lead to system performance fluctuations [2] and that the required ICXT level for a given outage probability may fluctuate 4 dB depending on whether (i) the ICXT and signal polarizations are aligned or not, and (ii) the product between the skew and the bit rate is much lower or much higher than one [6].

In this work, the degree of polarization (DoP) of the ICXT field induced by WC-MCFs is evaluated for on-off keying (OOK) signalling and for different conditions of laser phase noise. With this, the conditions in which the ICXT in WC-MCFs can be modelled by polarized or unpolarized components are identified.

II. SYSTEM MODEL

The DoP of the ICXT field induced in WC-MCFs is evaluated by numerical simulation. The ICXT is generated using the dual polarization model proposed in [7]. This model considers that the random fluctuations of the polarization and the random evolution of the ICXT along time are induced by random phase shifts (RPSs) associated with each phase matching point. The statistical features of the ICXT power generated by this model have shown good agreement with experimental results [7,8].

The RPSs are modelled by independent Wiener processes with the ICXT decorrelation time set to five minutes. The discrete coupling coefficient between the interfering and interfered core is -45 dB. The phase noise introduced by the continuous wave laser used to generate the optical signal launched into the interfering core is modelled by a Wiener process with zero mean and variance of $t\Delta\nu/(2\pi)$ for $t>0$, where $\Delta\nu$ is the laser linewidth. OOK signalling is launched into the interfering core and no signal is launched in the interfered core.

The DoP of the ICXT field induced in the interfered core is evaluated as [9]:

$$DoP=\frac{I_{pol}}{I_{tot}}=\sqrt{1-\frac{4|\boldsymbol{J}|}{\left(J_{xx}+J_{yy}\right)^2}} \qquad (1)$$

where I_{pol} and I_{tot} are, respectively, the intensity of the polarized part and the total intensity of the ICXT field, $|\boldsymbol{J}|$ is the determinant of the coherency matrix [9], $J_{aa}=\langle E_{XT,a}(t)E^{*}_{XT,a}(t)\rangle$ is an element of the coherency matrix corresponding to the intensity of the direction a (x or y), $\langle z\rangle$ is the time average value of z and z^{*} is the complex conjugate of z. $E_{XT,a}(t)$ is the ICXT field in direction a induced in the interfered core. The time average is evaluated using an integration time window needed to obtain stabilized DoP estimates. The DoP given by (1) provides the ratio of the polarized portion to the total ICXT intensity. DoP=1 means that the ICXT is a completely polarized wave. When 0<DoP<1, the ICXT may be regarded as a sum of an unpolarized and a polarized component.

III. RESULTS AND DISCUSSION

To assess the DoP of the ICXT field, we started by evaluating the ICXT for different time fractions. A time fraction is a short time period, much smaller than the ICXT decorrelation time, along which we may assume that the RPSs are constant. In this work, consecutive time fractions are separated by 5 minutes (identical to the ICXT decorrelation time) to ensure that the ICXT generated in different time fractions is weakly correlated. To evaluate only the impact of the skew-bit rate product (the skew is the relative time propagation delay between the interfered and interfering cores), $|S_{nm}|\times R_b$, on the DoP of the ICXT, we start the analysis by considering an ideal laser with no phase noise and three cases of the skew-bit rate product: $|S_{nm}|\times R_b<<1$, $|S_{nm}|\times R_b=1$ and $|S_{nm}|\times R_b>>1$. Fig. 1 shows the DoP

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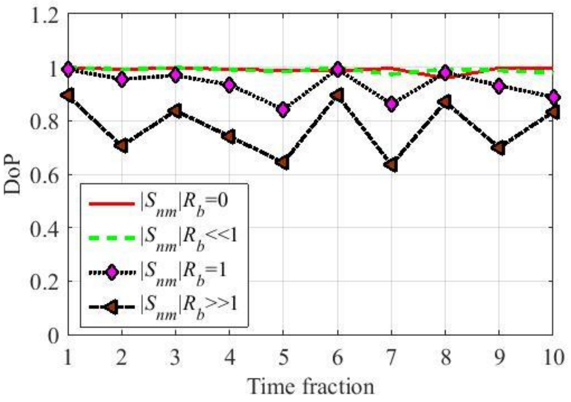

Fig. 1: DoP as a function of the time fraction for an ideal laser ($\Delta\nu$=0).

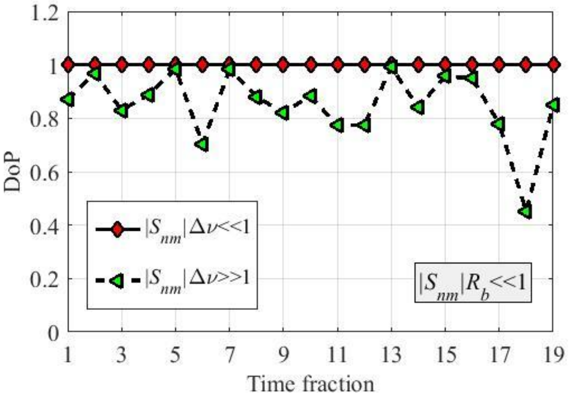

Fig. 2: DoP as a function of the time fraction for $|S_{nm}|\times R_b$<<1 and different cases of $|S_{nm}|\times\Delta\nu$.

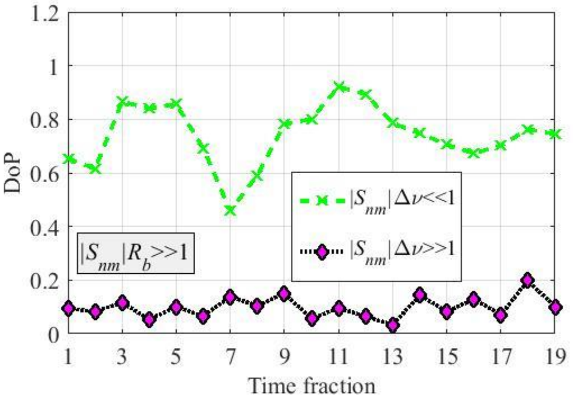

Fig. 3: DoP as a function of the time fraction for $|S_{nm}|\times R_b$>>1 and different cases of $|S_{nm}|\times\Delta\nu$.

of the ICXT field as a function of the time fraction for the three cases. The integration time used to evaluate the elements of the coherency matrix is 1 μs. The OOK signal bit-rate is 10 Gb/s and the extinction ratio is 10 dB. The inspection of Fig. 1 reveals two main conclusions. (i) The ICXT field is completely polarized as long as $|S_{nm}|\times R_b$<<1. This means that $E_{XT,x}(t)$ and $E_{XT,y}(t)$ are mutually coherent. (ii) When $|S_{nm}|\times R_b\geq 1$, the ICXT field is partially polarized and the fraction of the polarized part decreases when $|S_{nm}|\times R_b$ increases. The results of Fig. 1 suggest also that the fraction of the polarized part of the ICXT fluctuates along time and the fluctuations are higher for systems with higher $|S_{nm}|\times R_b$.

Fig. 2 depicts the DoP of the ICXT field for $|S_{nm}|\times R_b$<<1 considering MCF systems with $|S_{nm}|\times\Delta\nu$ <<1 and $|S_{nm}|\times\Delta\nu$ >>1. The integration time used to evaluate the elements of the coherency matrix is 1 ms due to the lower bit-rate used to achieve $|S_{nm}|\times R_b$<<1. The results of Fig. 2 show that the DoP decreases when $|S_{nm}|\times\Delta\nu$ >>1. This means that the phase noise may induce an unpolarized component on the ICXT.

Fig. 3 depicts results similar to Fig. 2, but for MCF systems with $|S_{nm}|\times R_b$>>1. The integration time used to evaluate the elements of the coherency matrix is 1 μs, as in Fig. 1. Fig. 3 shows that, for systems with $|S_{nm}|\times R_b$>>1, the phase noise of the laser employed to generate the optical signal transmitted in the interfering core plays an important role on the decrease of the fraction of the polarized part of the ICXT. Indeed, in systems with $|S_{nm}|\times R_b$>>1 and $|S_{nm}|\times\Delta\nu$ >>1, the DoP is close to zero and $E_{XT,x}(t)$ and $E_{XT,y}(t)$ tend to be mutually incoherent. In this case, the ICXT field is almost unpolarized.

These conclusions suggest that the analysis of the impact of the polarization misalignment between signal and ICXT on the performance of direct-detection systems performed in [6] should be extended to the case in which the ICXT field is completely unpolarized.

IV. CONCLUSION

The DoP of the ICXT in WC-MCFs has been evaluated for different system scenarios. For systems with $|S_{nm}|\times R_b$<<1 and negligible laser phase noise variance, the ICXT field is completely polarized. When $|S_{nm}|\times R_b$>>1 or $|S_{nm}|\times\Delta\nu$ >>1, the ICXT has a polarized and an unpolarized component. The fraction of the polarized component tends to zero when both the $|S_{nm}|\times R_b$ and $|S_{nm}|\times\Delta\nu$ increase. In that case, the ICXT field is almost unpolarized.

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