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Deposited in *Repositório ISCTE-IUL*:
2021-12-07

Deposited version:
Accepted Version

Peer-review status of attached file:
Peer-reviewed

Citation for published item:
Alves, T. M. F. , Rebola, J. L. & Cartaxo, A. V. T. (2021). Weakly-coupled MCF direct-detection OOK systems impaired by laser phase noise. In 2021 Optical Fiber Communications Conference and Exhibition (OFC). San Francisco, CA: IEEE.

Further information on publisher's website:
https://ieeexplore.ieee.org/xpl/conhome/9489393/proceeding

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Phone: +(351) 217 903 024 | e-mail: administrador.repositorio@iscte-iul.pt
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Weakly-Coupled MCF Direct-Detection OOK Systems Impaired by Laser Phase Noise

T. M. F. Alves, J. L. Rebola and A. V. T. Cartaxo
Instituto de Telecomunicações, Lisbon 1049-001, Portugal;
Iscte - Instituto Universitário de Lisboa, Lisbon 1649-026, Portugal
tiago.manuel.alves@iscte-iul.pt; joao.rebola@iscte-iul.pt; adolfo.cartaxo@iscte-iul.pt

Abstract: On-off-keying multicore fiber systems employing different lasers are experimentally investigated. Laser phase noise increases the instantaneous fluctuations of the crosstalk. DFB-based systems may require an additional crosstalk margin of 4 dB relative to ECL-based systems.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications

1. Introduction

Weakly-coupled multicore fiber (WC-MCF) technology combined with intensity modulation and direct-detection (IM-DD) systems are a promising solution to be employed in next generation short-reach networks as intra or inter data centers [1]. Compared with strongly-coupled MCFs, WC-MCFs generate low mean intercore crosstalk (ICXT) power levels. However, for unmodulated signals launched into the interfering cores, the short-term average crosstalk (STAXT) power, i. e., the average ICXT power measured at the output of the interfered core by an optical power meter along a very short time interval (≈100 ms), changes randomly over time and frequency [2,3]. These random fluctuations may lead to time periods in which very high ICXT peak power levels occur and, therefore, time intervals with possible service unavailability may happen [4-6]. With carrier-free signals, the ICXT power fluctuations can be relieved by using MCFs with high skew-bit rate product. In signals containing a strong optical carrier, like on-off keying (OOK), a high level of ICXT fluctuations occurs even for large skew and symbol rates [7]. Preliminary simulation results have also shown that the combined effect of the ICXT and laser phase noise can significantly affect the received eye-pattern and outage probability of 10 Gb/s OOK WC-MCF systems [8].

In this work, the impact of the laser phase noise on the instantaneous ICXT power, on the STAXT power and on the performance of DD-OOK WC-MCF systems is investigated. In particular, the impact of the product between the laser linewidth and the skew between cores on the STAXT is investigated by simulation and experimentally.

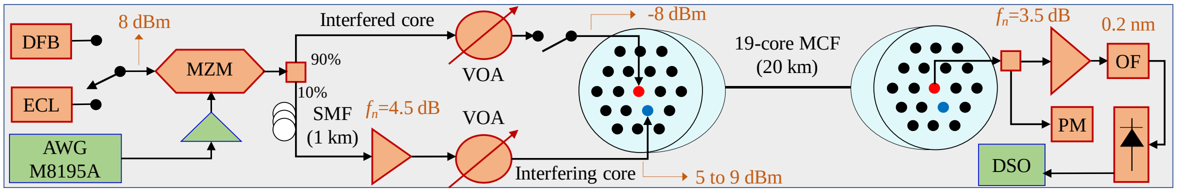
2. Setup

In this section, the setup of the 10 Gb/s DD-OOK WC-MCF system, shown in Fig. 1, used to analyze the impact of the laser phase noise on the STAXT and system performance by numerical simulation and experimentally is described. The experiments are performed with an HP8168F external cavity laser (ECL) with a narrow linewidth of 100 kHz and an off-the-shelf JDSU distributed feedback (DFB) laser with linewidth close to 10 MHz. The 10 Gb/s OOK waveform comprises 2^{14} bits and is generated by a 60 Gsamples/s Keysight M8195A. Electrooptic conversion is realized by a 10 GHz Mach-Zehnder modulator with extinction ratio of 10 dB. Two adjacent cores of a weakly-coupled homogeneous 19-core MCF with skew between cores of 8.8 ns and decorrelation time of a couple of minutes are used. With this, the skew-bit rate product is much higher than one which is preferable from the performance viewpoint in carrier assisted systems [6,7]. At the output of the interfered core, the STAXT power induced by the OOK signal is monitored by a power meter. For STAXT power measurements (performed with modulated data), the optical switch at the input of the interfered core is open. The ICXT-impaired OOK signal is then amplified, photodetected and captured by a 20 Gsamples/s real-time oscilloscope. Offline processing with digital filtering (4th-order Bessel low-pass filter with 8 GHz bandwidth) and error counting are performed. The STAXT power and BER were monitored continuously over several days with captures taken twice at each minute.

The setup used for numerical simulation is equivalent to that of Fig. 1. The phase noise introduced by the continuous wave laser is modeled by a Wiener process with zero mean and variance of $t\Delta\nu/(2\pi)$, where t represents the time and $\Delta\nu$ is the laser linewidth. The MCF simulation considers the dual polarization ICXT model [9]. This model considers the random fluctuations of the polarization and the random evolution of the ICXT along time is modelled by random phase shifts associated with each phase matching point (PMP) characterized by independent Wiener processes with the ICXT decorrelation time set to five minutes. Each time fraction, with duration of 3.3 μs, consists of a sequence of 2^{15} bits (frequency resolution of 30 kHz). The STAXT power is evaluated over hundreds of time fractions (time interval between fractions is 5 minutes) to adequately characterize the STAXT stochastic features.

3. Simulation results

Fig. 2(a) shows the evolution of the STAXT power, induced by a 10 Gb/s OOK signal (interfering core) and calculated at the output of the interfered core, along the time for an ideal laser (linewidth of 0 Hz), i. e., with the system being impaired only by the ICXT effect, and a laser with linewidth of 10 MHz (typical of DFB lasers) where



MCF features			
Cladding diameter	180 μm	Loss (incl. fans)	Between 14-18 dB
Core diameter	≈9 μm	Dispersion param.	≈20 ps/nm/km
Core pitch	32 μm	Skew	8.8 ns

AWG	Arbitrary waveform generator	MZM	Mach-Zehnder modulator
DFB	Distributed feedback	OF	Optical filter
DSO	Digital storage oscilloscope	PM	Power meter
ECL	External cavity laser	SMF	Single mode fiber
MCF	Multicore fiber	VOA	Variable optical attenuator

Fig. 1. Experimental setup used to investigate the performance of 10 Gb/s OOK IM-DD MCF-based systems operating with different lasers.

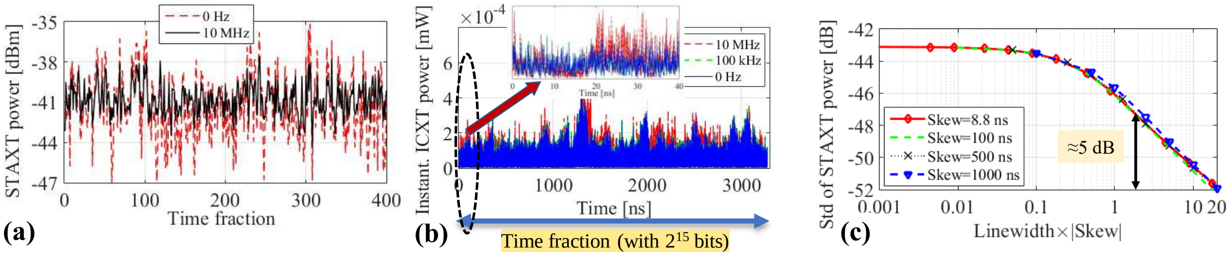


Fig. 2. (a) STAXT power as a function of the time for an ideal laser and a laser with linewidth of 10 MHz. (b) Instantaneous ICXT power as a function of the time in a time fraction for different laser linewidths. (c) Standard deviation of the STAXT power as a function of the product between the laser linewidth and the skew. In (a)-(c), the ICXT level is -28 dB and the results were obtained by simulation.

the combined effect of laser phase noise and ICXT is assessed. The ICXT level, defined as the ratio between the mean ICXT power and mean signal power at the output of interfered core, is close to -28 dB and the skew is 100 ns. The results suggest that the combined effect of laser phase noise and ICXT may significantly reduce the fluctuations of the STAXT power. Fig. 2(b) depicts the instantaneous ICXT power as a function of time for a given time fraction. The fluctuations of the instantaneous ICXT power increase when the laser linewidth (and, thus, when the phase noise variance) increases. Compared with the ideal laser, the standard deviation of the instantaneous ICXT power fluctuations, evaluated over the time fraction of Fig. 2(b), for lasers with 100 kHz and 10 MHz, is 0.1 dB and 1.1 dB higher, respectively. Despite the fluctuations of the instantaneous ICXT power increase with the laser phase noise, lasers with larger linewidths lead to a lower probability of having significant differences between the average ICXT power calculated over two different time fractions due to the averaging effect. Thus, the STAXT, that averages the instantaneous ICXT power over a time interval much longer than the bit duration, tends to present fluctuations with lower amplitude, as suggested by Fig. 2(a). In simulation, the averaging is performed over each time fraction of 3.3 μs. In experiments, it is performed over the integration time of the power meter. Fig. 2(c) depicts the standard deviation of the STAXT power as a function of the product between the laser linewidth and the skew between cores. For linewidth×|skew|<<1, the decrease of the standard deviation of the STAXT power is negligible (<<1dB). For the pair of cores of the MCF available in our lab with a skew of 8.8 ns, the decrease of the standard deviation of the STAXT power is limited to 0.4 dB when the laser linewidth increases from 0 Hz to 10 MHz. When linewidth×|skew|>>1, the decrease of the standard deviation of the STAXT power is close to 5 dB per decade of the linewidth×|skew|. When linewidth×|skew|≈1, the decrease of the standard deviation of the STAXT power is 3 dB. The reason to have a significant impact of the phase noise on the fluctuations of the STAXT power when linewidth×|skew|>>1 is that the skew is much higher than the time interval over which the laser phase noise is correlated (usually defined by the coherence time, $t_c=1/(\pi\times\Delta\nu)$). Therefore, the different contributions of the ICXT originated along the MCF to the optical field at the core output present further uncorrelation induced by the phase noise. When linewidth×|skew|<<1, the skew is shorter than the coherence time of the phase noise and, thus, the different contributions of the ICXT field are weakly affected by the phase noise. The impact of the laser phase noise on the mean of the STAXT power, evaluated also over 400 time fractions and obtained for skews between a few ns and 1 μs, showed that the mean of the STAXT power is neither affected by the laser phase noise nor by the skew.

4. Experimental Results

In this section, the impact of the laser phase noise on the STAXT power and performance of 10 Gb/s OOK systems is assessed experimentally. The experiments were conducted over several days in a temperature-controlled room environment. Fig. 3(a) depicts the evolution of the STAXT power along time when the ECL and the DFB laser are used. The STAXT power is normalized by the mean of the STAXT power evaluated over the monitoring period. The histograms of the STAXT power depicted in Fig. 3(a) for the two laser sources and the estimated Gaussian probability density function (PDF) with the same mean and variance as the experimental data are shown in

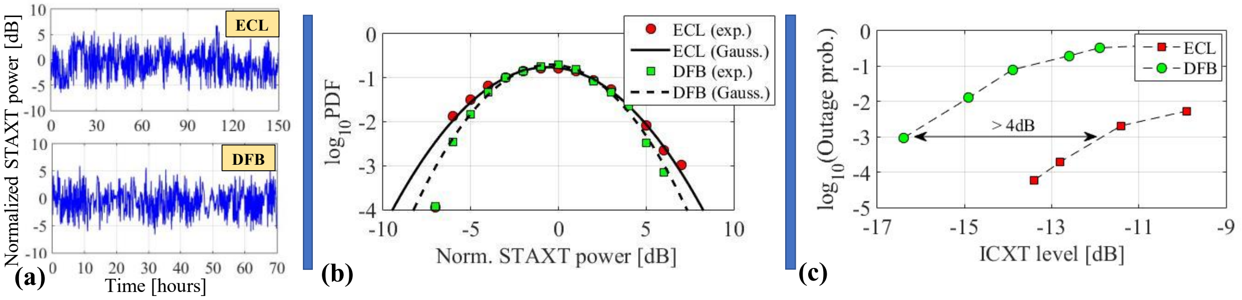


Fig. 3. (a) Evolution of the STAXT power along time, (b) histograms of the STAXT power, and (c) outage probability of the OOK signal obtained experimentally as a function of the ICXT level. Results for ECL and DFB laser are shown.

Fig. 3(b). Fig. 3(a) and (b) confirm that the STAXT power fluctuations decrease when lasers with higher linewidths are used. A 0.4 dB decrease between the standard deviation of the STAXT power measured with the ECL and the DBF laser is observed, which agrees with the simulation results of section 3. To investigate the impact of the laser source on the 10 Gb/s OOK system performance, the BER was monitored experimentally over more than two consecutive days. As low BER levels are obtained in most of the time and worse BER events, induced by high ICXT powers, occur sporadically [4,6], the performance of these systems should be characterized using the outage probability, i. e., the probability that the BER exceeds a given BER threshold. The outage probability was assessed from experimental BER measurements with a pre-FEC BER threshold of $1.5\times10^{-2}=10^{-1.82}$ (20.5% FEC). Fig. 3(c) depicts the outage probability measured considering the ECL and the DFB laser. These results show that 10 Gb/s DD-OOK MCF systems operating with DFB lasers may require an additional ICXT margin larger than 4 dB relative to systems operating with low linewidth ECLs, which is in line with preliminary simulation conclusions [8]. This worse outage probability observed for lasers with larger linewidths happens because the occurrence of errors on the OOK bit stream received in each time fraction depends on the instantaneous ICXT. As the laser phase noise leads to the increase of the instantaneous ICXT power fluctuations, then the BER degradation also increases. The results of Fig. 2 and 3 suggest that, for DD-OOK WC-MCF systems with |skew|×bit-rate>>1, the performance is inadequately characterized by the level of the STAXT power fluctuations. This occurs because the STAXT and outage probability are differently affected by the laser phase noise: (i) a decrease of the STAXT power fluctuations induced by the increase of the laser phase noise is observed, and (ii) when the laser phase noise increases, the outage probability suffers from additional degradation caused by the larger fluctuations of the instantaneous ICXT power.

5. Conclusion

DD-OOK WC-MCF systems impaired by the combined effect of the laser phase noise and ICXT have been investigated. It has been shown that the STAXT and outage probability are differently affected by the laser phase noise and that the level of the fluctuations of the STAXT power may be an inadequate metric to qualitatively characterize the system performance. When the laser phase noise variance increases: (i) the decrease of the standard deviation of the STAXT power fluctuations is close to 5 dB per decade of linewidth×|skew|, due to the STAXT averaging effect; and (ii) the fluctuations of the instantaneous ICXT power increase and the outage probability suffers from additional degradation caused by these larger ICXT fluctuations. For the same outage probability, experimental results have shown that DD-OOK WC-MCF systems operating with DFB lasers may require an additional ICXT margin exceeding 4 dB relative to ECL-based systems.

6. Acknowledgement

FCT from Portugal by funding this work under the DigCore/UIDP/50008/2020, UIDB/EEA/50008/2020 and IF/01225/2015 projects.

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