Enhanced Self-Coherent OFDM by the Use of Injection Locked Laser

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Abstract: An injection-locked laser based pilot carrier enhancement technique is proposed for self-coherent OFDM. An improvement of 2.2 dB is observed when compared to Fabry-Perot filter based self-coherent OFDM.

OCIS codes: 060.4510 Optical communications; 060.1660 Coherent communications; 140.3520 Lasers, injection locked

1. INTRODUCTION

The vision of providing ubiquitous high-speed access to information has led to extensive research in advanced modulation formats. Among others, orthogonal frequency division multiplexing (OFDM) has received considerable interest because of the possibility to scale to higher level modulation formats and to realize next generation agile optical networks [1,2]. With the rekindled interest in coherent receivers, much of the effort has been focused on the digital signal processing (DSP) which is a key technology for realizing 100 Gb/s and beyond optical transmission systems. In a coherent optical (CO-) OFDM system, phase noise represents one of the main impairments that must be compensated for. The RF aided phase noise compensation (RF-PNC) scheme has shown to be a robust compensation method for both laser linewidth [3] and fiber based non-linearity [4]. Nevertheless, the complexity of implementing RF-PNC increases the requirements of the DSP, which is already limited in speed and processing capabilities. On the other hand, Fabry Perot filter based self coherent optical (SCO-) OFDM does not require phase noise compensation reducing the complexity of DSP and no local oscillator (LO) is required at the receiver [5]. However, the performance of such a receiver is limited due to ASE noise at the carrier wavelength, especially since an optical amplifier is required at the receiver to ensure sufficient power for self-coherent detection [6].

In this paper we propose the use of an injection-locked laser (ILL) [7, 8] to retrieve the frequency and phase information from the extracted carrier without the use of an amplifier. Similar to the RF-PNC concept for CO-OFDM, ILL based self coherent OFDM (ILL-OFDM) is realized by sending an optical carrier along with the OFDM signal. At the receiver, the carrier is extracted from the OFDM signal using a Fabry-Perot tunable filter (FP-TF) and an ILL is used to significantly amplify the carrier and reduce intensity and phase noise. Unlike in [5] an amplifier is not required; the pilot carrier is enhanced using an ILL. In contrast to CO-OFDM, such a system supports low-cost broad linewidth lasers and benefits with lower complexity in the DSP as no carrier frequency estimation and phase noise compensation is required. Comparing the back-to-back performance of such a system to SCO-OFDM, a significant improvement of 2.2 dB in required OSNR is seen resulting in only 0.5 dB residual penalty with respect to CO-OFDM employing RF-PNC technique.

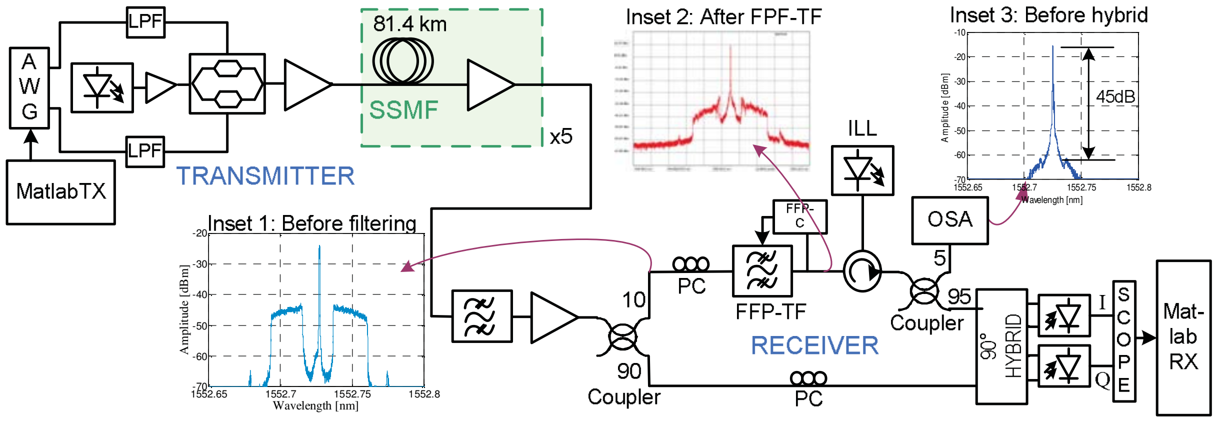

Fig. 1: Schematic of injection locked laser based self coherent optical OFDM system with Inset 1: optical spectrum before carrier extraction, Inset 2: optical spectrum after FPF-TF and Inset 3: optical spectrum after carrier extraction; FP-TF/C: Fabry-Perot tunable filter/controller, PC: polarization controller, ILL: injection locked laser, OSA: optical spectrum analyzer.

2. EXPERIMENTAL SETUP

The experimental configuration for the transmitter, link and receiver of the ILL-OFDM system is illustrated in Fig. 1. In the experiments, an arbitrary waveform generator (AWG) was used at a sampling rate of 10 GSamples/s to generate a continuous baseband signal. The OFDM baseband waveform was calculated offline and uploaded into the AWG. A low-pass filter (LPF) after the AWG with 4.4 GHz bandwidth was used to suppress any aliasing products. For the generation of the OFDM signal, a 256 FFT size was used, from which 148 subcarriers were used as data. The modulation format was a non-rectangular 8-QAM constellation on each subcarrier. 64 subcarriers around the DC were padded with zeros to make place for the insertion of an optical carrier/ pilot-tone. A cyclic prefix overhead of 6.25% was used to increase ISI tolerance. The net and nominal data rates were ~14.9 Gb/s and ~15.3 Gb/s, respectively. A laser with specified linewidth of 100 kHz was used at the transmitter to generate a continuous wave signal that was subsequently modulated with the OFDM signal by an IQ-Mach–Zehnder modulator (IQ-MZM). The IQ-MZM was biased such that the optical carrier was not totally suppressed at the transmitter leaving a carrier at the center of the spectrum as shown in the Inset 1 of Fig.1.

The transmission link consisted of 5 spans of 81.4-km standard single mode fiber (SSMF) without any dispersion compensation. After every span, an erbium-doped fiber amplifier (EDFA) was used for amplification. At the receiver, a coupler was implemented to separate the OFDM signal path from carrier extraction stage. In the carrier extraction path, a FP-TF filter with a 3-dB bandwidth of 120 MHz was employed to separate the carrier from the OFDM signal. With this filter, a guardband of 1.3 GHz was used in the experiment to easily filter out the optical carrier at the receiver. Note that the center wavelength of the FP-TF was aligned to that of the laser. In order to cope with laser drifts, an automated feedback loop was realized to actively tune the center frequency of the FP-TF to the optical carrier using an external Fabry-Perot controller. The spectrum after FP-TF is shown in Inset 2 of Fig. 1. Compared to the setup in [5], where a second FP-TF was used to suppress the OFDM signal leaking into the filtered carrier and amplifiers were used to amplify the carrier, in this setup only a single FP-TF was required. This is because an ILL was used to transfer the frequency and the phase information of the carrier to the laser via injection locking and enhance the pilot power. The ILL was an AlInGaAs multiple quantum well discrete-mode laser diode with rigid geometry [9]. In Inset 3 of Fig. 1, the optical spectrum after ILL is shown. It can be seen that after the ILL, the OFDM signal leaking into the filtered carrier was suppressed to more than 40 dB (measured at a resolution of 0.8 pm). The output of the ILL was then sent to the 90° optical hybrid and used as LO. The polarization of the extracted optical carrier and optical OFDM signal were aligned with polarization controller in the signal path before detection. The bandwidth of the oscilloscope was 16 GHz and the sampling frequency was 50 GSamples/s. For the CO-OFDM systems, an external cavity laser (ECL) with 100-kHz typical linewidth was used as LO and in the DSP, RF-PNC [1] was used.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In this paper, the performance of ILL-OFDM is compared to that of CO-OFDM with RF-PNC scheme and SCO-OFDM. The power into the injection locked laser is a crucial parameter to be optimized for ILL-OFDM system. Fig. 2(a) shows the influence of input signal power to the laser on the bit-error-rate (BER) in a back-to-back case with optical signal-to-noise ratio (OSNR) fixed at 12 dB. For low input power two phenomena occurs. Firstly, since the laser does not have an isolator it is vulnerable to reflections. Secondly, the injection locking area also becomes extremely narrow such that, practically, the system is vulnerable to any frequency drifts that may originate from the

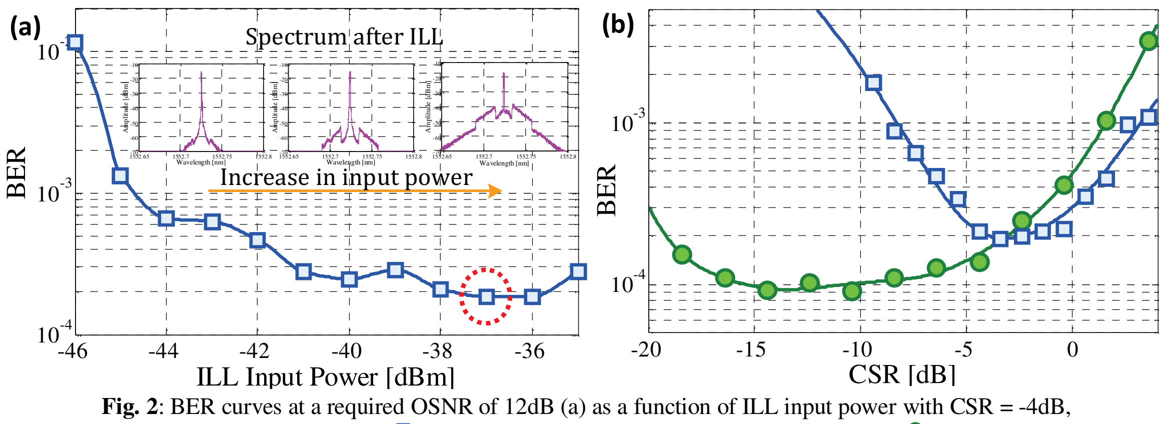

Fig. 2: BER curves at a required OSNR of 12dB (a) as a function of ILL input power with CSR = -4dB, (b) as a function of CSR for **ILL-OFDM** with ILL Input Power = -37dBm and **CO-OFDM**

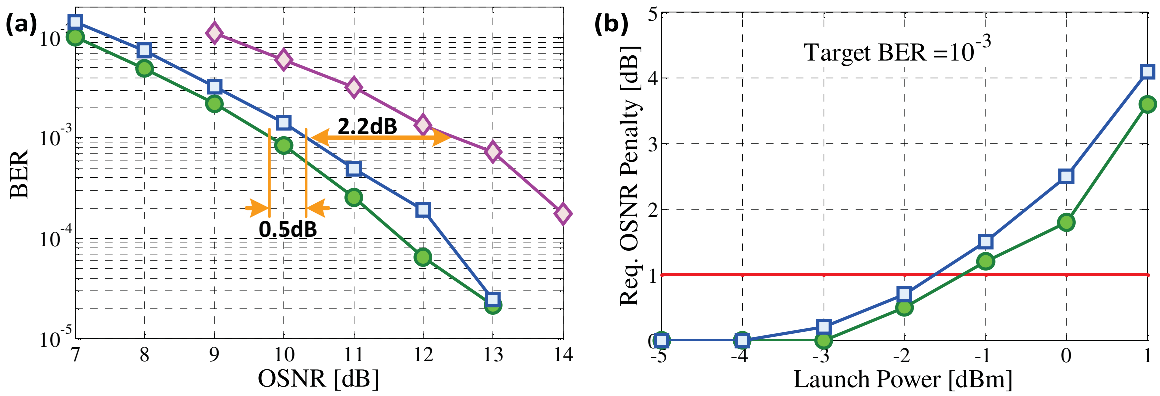

Fig.3: (a) BER as a function of OSNR for back-to-back scenario for □ **ILL-OFDM** at ILL Input Power = -37dBm, CSR = - 4dB, ● **CO-OFDM** at CSR = -10.2dB and ◇ **SCO-OFDM** at CSR = -5.4dB
(b) Required OSNR penalty as a function of the launch power after 400km transmission for □ **ILL-OFDM** at CSR = -4dB, ILL Input Power = -37dBm and ● **CO-OFDM** at CSR = -10.2dB

transmit laser. Both these phenomena are responsible for increase in BER. The optimum value of -37 dBm is seen from the figure and is kept at this point for all the following results related to ILL-OFDM. At powers above the optimum, due to leaking of OFDM signal into the laser, (as seen from the rightmost spectrum in the inset of Fig 2(a)) the BER increases. The power of the carrier with respect to the power of the OFDM signal, called carrier-to-signal ratio (CSR), has a strong influence on the system performance as well. In Fig. 2(b), the influence of CSR on the BER performance is shown in a back-to-back configuration. The OSNR in this measurement is kept constant at 12 dB and the optimum CSR is seen at -10.2 dB and -4 dB, for CO-OFDM and ILL-OFDM, respectively. When the CSR is below the optimum, the optical carrier is too weak and ASE noise limits the effectiveness of phase noise compensation. For high CSR, the relative power of the OFDM signal becomes too low and hence the performance gets worse. For all the following measurements, the CSR values are set to the optimum value.

Fig. 3(a) depicts the back-to-back BER performance as a function of the OSNR. The required OSNR for a BER of 10^{-3} is 9.8 dB and 10.3 dB for CO-OFDM and ILL-OFDM, respectively. Compared to SCO-OFDM [5], a 2.2-dB improvement is seen in ILL-OFDM. In SCO-OFDM, the extracted optical carrier is impaired by ASE noise arising from amplifiers. The increase in performance in ILL-OFDM can be attributed to the fact that ILL cleans up the carrier from the amplitude noise induced due to OSNR degradation and enhances its power without the need to amplify. Subsequently it can be said that ILL-OFDM does not only give a 2.2-dB benefit over SCO-OFDM but also removes the requirement of a second FP-TF and amplifiers. Finally, Fig. 3(b) shows the nonlinear tolerance of CO-OFDM and ILL-OFDM after 400-km transmission. The launch power is varied from -5 dBm to 1 dBm. The y-axis of the plot depicts the OSNR penalty for a BER of 10^{-3}. As expected for low launch powers no OSNR penalty is present. As the launch power is increased, the nonlinearities come into play. Allowing a 1-dB penalty in required OSNR, the maximum tolerable launch power is found to be -1.2 dBm and -1.7 dBm CO-OFDM and SCO-OFDM, respectively.

3. CONCLUSION

In this paper, an injection-locked laser based pilot enhancement scheme is proposed and compared to CO-OFDM and SCO-OFDM. A residual penalty of 0.5 dB is seen when the performance of such a system is compared to CO-OFDM and a drastic improvement of 2.2 dB is observed when compared to SCO-OFDM. The proposed system benefits from lower DSP complexity and does not require additional amplifiers.

4. References

[1] S L. Jansen et al., '*Application scenarios for optical OFDM*', SPPcom, 2010 (invited).
[2] D. Qian et al., '*Transmission of 115×100G PDM-8QAM-OFDM Channels With 4bits/s/Hz*', in Proc. ECOC, Th.13.K.3, 2011.
[3] S. Randel et. al., '*Analysis of RF-Pilot-based Phase Noise Compensation for Coherent Optical OFDM*', PTL vol.22, no.17, 1288-90, 2010.
[4] L. Du et al., '*Experimental Demonstration of Pilot-based XPM NL Compensator for CO-OFDM Systems*', in Proc ECOC, Th.11.B.4, 2011.
[5] S Adhikari et. al., '*Experimental Investigation of SCO-OFDM System Using FP-Filter for Carrier Extraction*', in Pro ECOC, Tu.4.A.1, 2010.
[6] J. Arnaud, '*Enhancement of optical receiver sensitivities by amplification of the carrier*', IEEE JQE , vol.4, no.11, pp. 893- 899, 1968.
[7] C.J. Buczek et. al., '*Laser injection locking*', Proc. IEEE, 61,1411-1431, 1973.
[8] S.K. Ibrahim et. al., '*Novel real-time homodyne coherent receiver using a feed-forward carrier extraction scheme*', Opt. Exp., Vol.19, Issue 9, pp. 8320-8326, 2011.
[9] B. Kelly et. al., '*Discrete mode laser diodes with very narrow linewidth emission*', Electronics Letters, Vol.43 Issue.23, 2007.