

# Experimental Investigation of Self Coherent Optical OFDM Systems Using Fabry-Perot Filters for Carrier Extraction

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**Abstract** We experimentally demonstrate self coherent optical OFDM transmission with IQ demultiplexing employing a Fabry-Perot-tunable filter for the extraction of the optical carrier. The performance is investigated and compared to a conventional CO-OFDM.

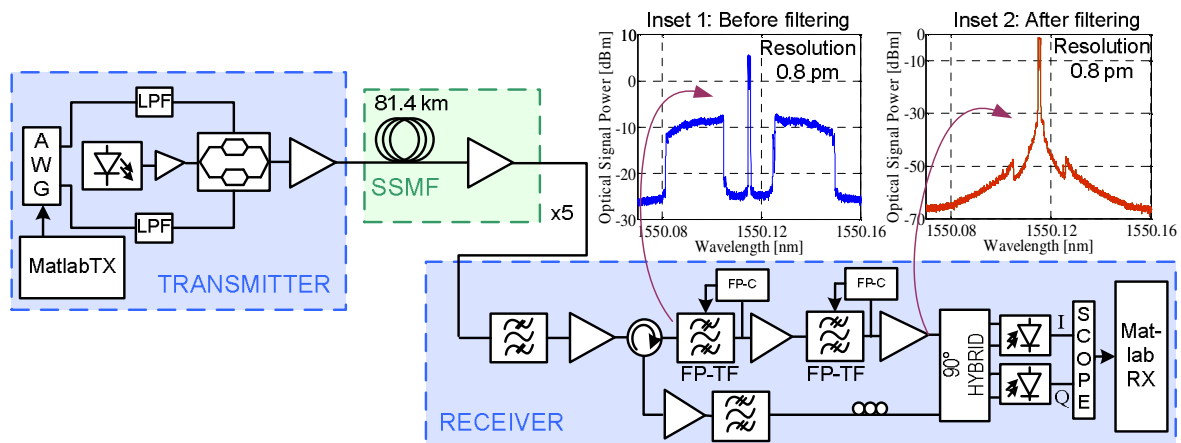
## Introduction

With the descent of next generation 100-Gb/s Ethernet protocol, conventional non return-to-zero (NRZ) is perishing and the optical communication society is advancing with massive research to find the next generation spectrally efficient advanced modulation format. A combination of coherent receiver with digital signal processing (DSP) is emerging as a promising solution for 100G upgrades. One of these propitious modulation formats employing coherent detection and DSP is coherent optical orthogonal frequency division multiplexing (CO-OFDM) [1]. CO-OFDM offers a virtually unlimited tolerance against linear impairments of an optical fiber and is easily scalable to higher level modulation formats [1, 2].

However, in CO-OFDM system, phase noise represents a major challenge that must be compensated for [3, 4]. In [5], the RF aided phase noise compensation (RF-PNC) scheme has been investigated that allows for a considerable increase in tolerable laser linewidth. Nevertheless, the complexity of implementing RF-PNC technique increases the requirements of the DSPs, which are already

limited in speed and processing capabilities. Conversely, self coherent optical (SCO-) OFDM is an interesting alternative to conventional CO-OFDM (CCO-OFDM) as it does not require phase noise compensation; consequently reducing the DSP complexity. Furthermore, no local oscillator (LO) is required at the receiver. Several concepts of SCO-OFDM have been proposed [6-8]. Similar to the RF-pilot-tone phase noise compensation concept for CCO-OFDM [3, 5], SCO-OFDM is realized by sending an optical carrier (or pilot-tone) along with the OFDM signal. At the receiver, the optical carrier is extracted from the OFDM signal and used as an LO using heterodyne or homodyne detection. Such a system effortlessly compensates for transmitter laser linewidth as well as phase noise generated by fiber nonlinearities.

In this paper, we propose the use of Fabry-Perot-tunable filters (FP-TF) with very narrow bandwidth to realize SCO-OFDM. Using these filters we realize the first SCO-OFDM experiment with IQ demultiplexing. The performance of such a system is investigated and compared to a CCO-OFDM employing RF-PNC technique.



**Fig. 1:** Schematic of self coherent optical (SCO-) OFDM system with Inset 1: optical spectrum before FP-TF series and Inset 2: optical spectrum after FP-TF series; FP-TF/C: Fabry-Perot-tunable filter/controller.

## Experimental Setup

The experimental configuration for the transmitter, link and receiver of the SCO-OFDM system is illustrated in Fig. 1. In the experiments, an arbitrary waveform generator (AWG) is used at a sampling rate of 10 GSamples/s to generate a continuous baseband signal. The OFDM baseband waveform is calculated offline and uploaded into the AWG. A low-pass filter (LPF) after the AWG with 4.4 GHz bandwidth is used to suppress any aliasing products.

For the generation of the OFDM signal, a 256 FFT size is used, from which 148 subcarriers are effectively used as data. The modulation format is a non-rectangular 8-QAM (quadrature-amplitude-modulation) on each subcarrier. 64 subcarriers around the DC are padded with zeros to make place for the insertion of an optical carrier/pilot-tone. A cyclic prefix overhead of 6.25% is used to increase ISI tolerance. The net and nominal data rates are  $\sim 14.9$  Gb/s and  $\sim 15.3$  Gb/s, respectively.

A laser is used at the transmitter to generate a continuous wave (CW) signal that is subsequently modulated with the OFDM signal by a super Mach-Zehnder modulator (sMZM). Similar to the CO-OFDM modulation format discussed in [7], the sMZM is biased such that the optical carrier is not totally suppressed at the transmitter.

The transmission link consists 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) is used for amplification.

At the receiver, a cascade of two FP-TF filters is employed to separate the carrier from the OFDM signal. The FP-TF is a narrowband bandpass filter that transmits the optical carrier and rejects the OFDM signal. In this experiment FP-TF filters are chosen as bandpass filter because of their high Q-value and narrow bandwidth. The Q-value of the filter is important as it enables a narrow guardband between the optical carrier and the OFDM signal making the separation easy. The first and second FP-TFs have 3-dB bandwidth of 250 MHz and 460 MHz, respectively. The Q-value is approximately 20.5 dB. With these filters a guardband of 1.3 GHz was used in the experiment to easily filter out the optical carrier at the receiver.

In Inset 1 and 2 of Fig.1, the optical spectrum of the signal before and after filtering is shown respectively. Clearly, after the second FP-TF, the OFDM signal leaking into the filtered carrier is suppressed to around 50 dB adding up to a total suppression of 35 dB (measured at a resolution of 0.8 pm). Note that the center

wavelength of the FP-TF must be perfectly aligned with that of the laser. In order to cope with laser drifts, an automated feedback loop is realized to actively tune the center frequency of the FP-TF to the optical carrier using an external Fabry-Perot controller (FP-C).

A circulator is implemented to recover the reflected OFDM signal from the FP-TF. The polarization of the extracted optical carrier and optical OFDM signal are then aligned with polarization controller. Homodyne detection is realized with a  $90^\circ$  optical hybrid. The succeeding balanced photo detectors (BPD) convert the received optical signal to electrical in-phase (I) and quadrature-phase (Q) signals. At the receiver, after homodyne detection, the signal is sampled with a real-time oscilloscope and processed off-line. The bandwidth of the oscilloscope is 16 GHz and the sampling frequency is 50 GSamples/s.

In this paper, the performance of SCO-OFDM is compared to that of CCO-OFDM with RF-PNC scheme. For the CCO-OFDM system, an external cavity laser (ECL) with 100-kHz typical linewidth is used as LO and the OFDM signal is directly fed into the  $90^\circ$  hybrid.

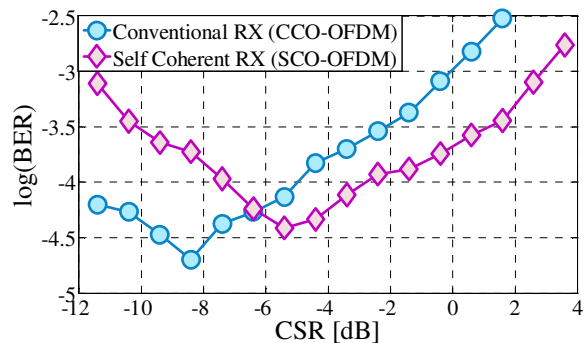
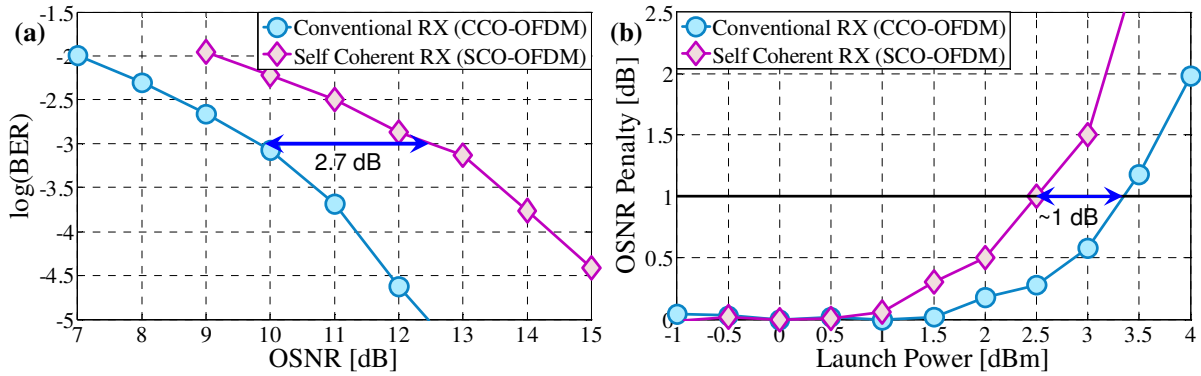


Fig. 2: BER as a function of CSR.

## Experimental Results and Discussion

For SCO-OFDM measurements, the optical power of the filtered carrier and OFDM signal at the input of  $90^\circ$  hybrid is kept at 7 dBm and 0 dBm, respectively, which was found to be the optimum value. Similarly, for CCO-OFDM the optimal optical power of the LO and OFDM signal is found to be 15 dBm and 0 dBm, respectively. These values are kept constant for all the following measurements.

Both in SCO-OFDM and CCO-OFDM employing RF-PNC, an optical carrier (or pilot-tone) is sent along with the OFDM signal. This optical carrier is used at the receiver for phase noise compensation. For SCO-OFDM, the optical carrier is extracted from the OFDM signal for homodyne detection. While for CCO-OFDM the optical carrier is heterodyne detected and digitally used as a pilot-tone for phase noise compensation [5]. For both modulation formats,



**Fig. 3:** (a) BER as a function of OSNR for back-to-back scenario, (b) Required OSNR penalty as a function of the launch power after 400km transmission.

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. Note that, this value is referred to as pilot-to-signal power ratio (PSR) in [3]. In Fig. 2, the influence of this CSR on the bit-error-rate (BER) performance is shown in a back-to-back configuration.

The optical signal-to-noise ratio (OSNR) in this measurement is kept constant at 12 dB and 15 dB for CCO-OFDM and SCO-OFDM, respectively. The optimum CSR for CCO-OFDM and SCO-OFDM is located at -8.4 dB with BER at  $2.0 \times 10^{-5}$  and -5.4 dB with BER at  $3.9 \times 10^{-5}$ , respectively. When the CSR is below the optimum, the optical carrier is too weak and amplified spontaneous emission (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 12.5 dB for CCO-OFDM and SCO-OFDM, respectively. The 2.7-dB difference between CCO-OFDM and SCO-OFDM is largely caused by the fact that in SCO-OFDM, the extracted optical carrier is impaired by ASE noise and is used for coherent detection. This noisy carrier leads to distortions in the real and imaginary parts of the constellation. While in conventional CO-OFDM, the pilot tone is used for digital phase noise compensation and a clean LO, that induces only phase noise, is used for coherent detection. In addition, the bandwidth of the FP-TF used in SCO-OFDM is significantly wider than the digital filter that is implemented for CCO-OFDM phase noise compensation. The wider the filter bandwidth, the more noise is added to the carrier. Subsequently, it can be inferred that with the use of lower bandwidth, the

performance will most likely get better.

Finally, Fig. 3(b) shows the nonlinear tolerance of CCO-OFDM and SCO-OFDM after 400-km transmission. The launch power is varied from -1 dBm to 4 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 3.4 dBm and 2.5 dBm for CCO-OFDM and SCO-OFDM, respectively.

## Conclusions

In this paper, we have reported the first self-coherent optical OFDM system with IQ demultiplexing. A FP-TF is used for extracting the optical carrier because of its high Q-value which relaxes the bandwidth of the guardband between the carrier and OFDM signal. The guardband of only 1.3 GHz was used in the experiment. Compared to conventional CO-OFDM employing RF-PNC scheme, a 2.7 dB OSNR penalty is observed and a reduction of ~1 dB in nonlinear tolerance. By reducing the FP-TF bandwidth the performance of SCO-OFDM can most likely be further improved.

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