Polarization-Independent Optical Injection Locking

Jokhakar Jignesh[1], Bill Corcoran[1, 2] and Arthur J. Lowery[1, 2]
[1]*Electro-Photonics Lab, Dept. of Electrical and Comp. Syst. Eng., Monash University, Clayton, VIC 3800, Australia*
[2]*Centre of Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Australia*
jignesh.jokhakar@monash.edu

Abstract: A pluggable system making optical injection locking independent of the incoming signal's polarization-state is proposed and experimentally verified to maintain stable locking for random polarizations without performance loss in carrier recovery for coherent optical communications.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (140.3520) Lasers, injection-locked

1. Introduction

Optical injection locking (OIL) has been extensively studied as a method for replicating the phase information of an incoming optical carrier [1-3, 5]. In optical communication systems, this recovered carrier can then be used as a local oscillator (LO) in the coherent receivers to remove the carrier frequency and laser phase offsets [1-3]. In comparison with the optical phase lock loops (OPLL) that are limited by their electrical loop bandwidths, OIL can provide a wide capture range for several GHz of carrier frequency offsets (CFO) [4]. However, in order to maintain the locked state (zero CFO) of the injection locked laser, the polarization of the incoming signal must be constant and aligned with that of the free running signal of the injection laser. The variations in the polarization of the injected signal misaligns the incoming wave with the polarization of the injection locked laser oscillation and the lock is lost. This creates problems for implementation of OIL in practically deployed systems where the signal's polarization changes frequently and randomly. Polarization-independent digital signal processing algorithms that recover the carrier state of the signal are standard in modern coherent systems. However, these are limited in the bandwidth over which the carrier's phase fluctuations can be recovered. This has motivated us to design a pluggable module that can be simply added in front an OIL setup to take care of the incoming polarization. In this paper, we propose one such design and present the experimental performance of the system before and after adding this pluggable module. We observed that both systems performed similarly without any loss of performance, while the system with the proposed module performed in spite of a fluctuating random polarization of the incoming signal

2. Proposed module design and experimental setup

The proposed module design is shown in the inset in Fig. 1. The underlying concept of the module is that it aligns the unknown state of polarization of the incoming signal to a known fixed polarization state, which is aligned to the signal of the injection laser. To achieve this, the incoming signal is split into its horizontal and vertical polarization components with a polarization beam splitter (PBS). In this case, both the vertical ($\hat{v}$) and horizontal ($\hat{h}$) components of the incoming signal are coupled to the slow axis of the polarization maintaining fibers (PMFs) at the PBS outputs.

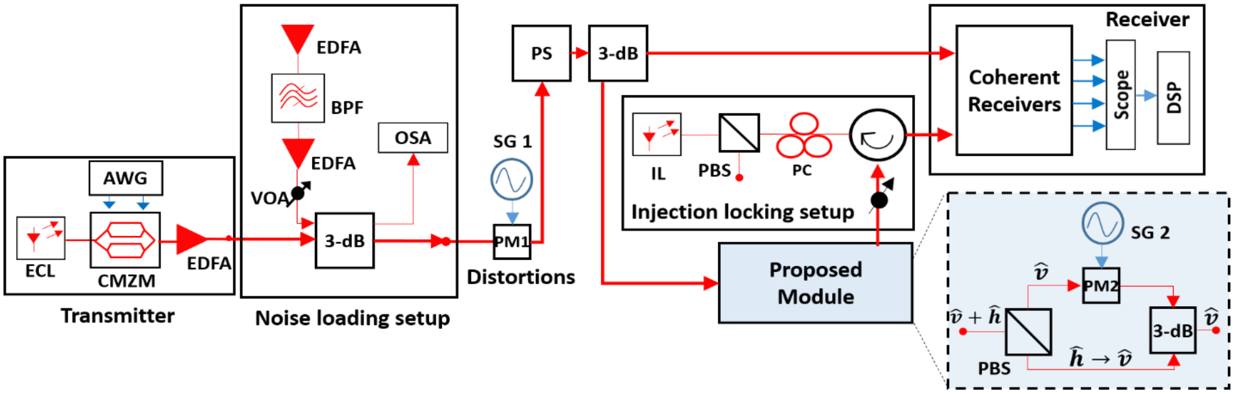

Fig. 1. Experimental setup and proposed module design; ECL: external cavity laser, AWG: arbitrary waveform generator, CMZM: complex Mach-Zehnder modulator, EDFA: erbium-doped fiber amplifier, VOA: variable optical attenuator, PM1/2: phase modulator, PC: polarization controller, BPF: band pass filter, PBS: polarization beam splitter, DSP: digital signal processing, IL: injection laser, SG: signal generator, PS: polarization scrambler.

Since both components of the signal are now aligned to the slow axis of different output arms of the PBS, a polarization-maintaining 3-dB coupler combines them together aligned to the slow axis of the output PMF, providing an output aligned to the slow axis regardless of input polarization state. However, this set-up also acts as an interferometer, and if it settles in a null, the injection locking will be lost. To avoid this, a phase modulator (PM2 in Fig.1) is added in one of the arms of the proposed module driven by a low frequency signal (400 kHz). As a result, the phase difference between the two signals in the two arms of the module are constantly changing, which prevents long-time destructive interference in the 3-dB coupler. Unfortunately, the phase modulation in one arm causes low frequency (400 kHz) amplitude modulations in the signal at the output of the 3-dB coupler. Fortunately these amplitude modulations are suppressed by a feature of OIL, where low-frequency amplitude modulation is rejected [5].

We proved the concept experimentally in multiple steps. First, a 100-MHz sinusoidal phase modulated signal was transmitted directly through the OIL setup with injection ratio of -50-dBm, and the peak-to-peak phase swing of the recovered signal was measured in reference to that of the signal detected in a simple homodyne setup without OIL. The polarization state of the signal injected into the OIL setup was changed using a Novoptel EPX1000 polarization scrambler (PS). This was done to ensure that the proposed module does not cause any suppression of the modulation or unlocking with changing polarization state. The polarization state of the incoming signal was varied first by changing the rotation angle of a half-wave plate (HWP) in the PS, then the full-wave plate (FWP), and then both of them simultaneously to cover random points on the Poincaré sphere. Figures 2(a) and 2(b) show that more than 97% of the input phase swing was transferred through the OIL setup independent of the polarization of the incoming signal.

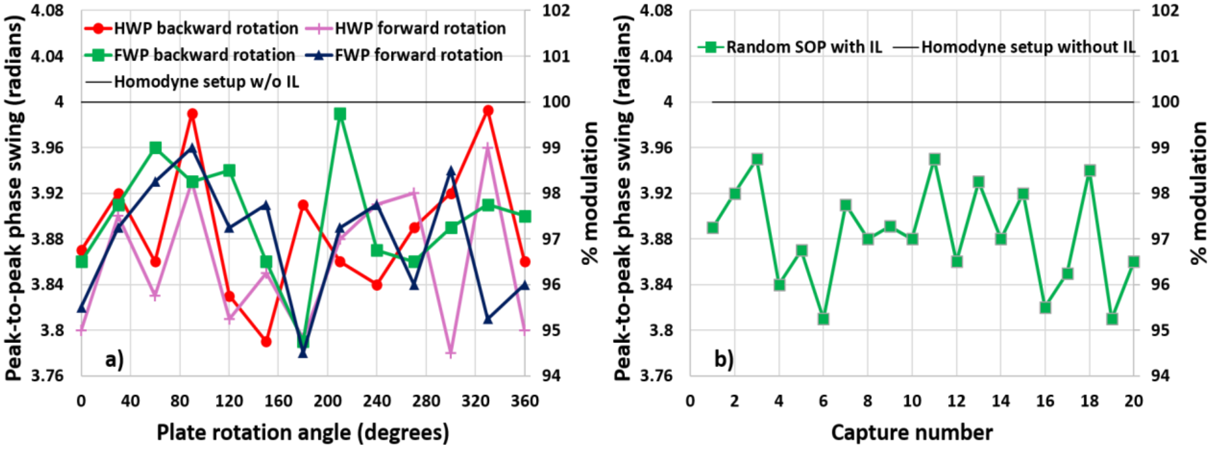

Fig. 2. Peak-to-peak phase swing of the recovered signal and % modulation transfer through OIL setup *vs.*: a) rotation angle of half wave plate and full wave plate of the polarization scrambler; b) for 20 data captures each with a random SOP. SOP: state of polarization.

The second part of the experimental confirmation of the concept includes transmission of an optical OFDM signal through the setup shown in Fig. 1. A 25-Gbaud QPSK OFDM electrical signal with 100 subcarriers and 156-point FFT length was generated using an arbitrary waveform generator to drive an optical IQ modulator. A central guard band of 2.5 GHz (10 sub-carriers) was added to keep a clear spectrum containing the optical carrier, preventing transfer of the modulated signal through OIL. Optical noise covering a 200-GHz bandwidth was added to vary the received OSNR. The noise loaded signal was distorted using a phase modulator (PM1) that was driven by a 1-MHz sinusoidal electrical signal. These distortions were added to provide an indication as to whether the phase drift of a high linewidth laser on the transmitter side could be transferred through OIL, to verify the benefit of using optical injection locking in self-homodyne setup over coherent receiver with a separate free running LO. After adding the distortions, the polarization of the signal is scrambled using a Novoptel EPS1000 polarization scrambler. The scrambled signal is then split using a 3-dB coupler, where one arm is connected to the proposed module followed by an OIL setup and the other arm is directly connected to the signal input of a 25-GHz electrical bandwidth integrated coherent receiver. The outputs of the coherent receiver were connected to a 40-GSa/s 28-GHz bandwidth digital signal oscilloscope (DSO). The data recovery algorithms were run as offline DSP. For reference, the OFDM signal was received in a standard intradyne receiver set up without polarization scrambling or OIL and the *Q* performance was measured, both with (pink curve in Fig. 3a) and without (red curve) phase distortion added to the signal. With distortion, the *Q* performance showed deterioration, with a 5-dB penalty at 20-dB OSNR. With the injection locking system in place, with an injection ratio of -50 dB, a standard OIL setup (without the polarization locking addition) was used to provide as a local oscillator and the *Q* performance was measured. As expected, this setup with OIL was able to negate the effect of phase distortions from PM1 (blue curve in Fig. 3.a.), providing similar performance to the undistorted intradyne received signal (red curve in Fig. 3a). However, the standard OIL setup is still sensitive to polarization, and so we add the proposed module before the OIL, and randomize the incoming polarization of the signal. The phase modulator PM2 in the module is driven with a 400-kHz sinusoidal signal. With the addition of the proposed module, the system performance (green curve in Fig. 3a) was observed to be again similar to the reference (red curve in Fig. 3a) without penalty despite of distortions added before the 3-dB coupler. In case when the distortions are present only on the LO and not the signal, the *Q* performance again shows a degradation (orange curve in Fig. 3a). This then shows that using the injected locked laser as a local oscillator effectively suppresses phase distortion, avoiding the need for digital signal processing in the receiver.

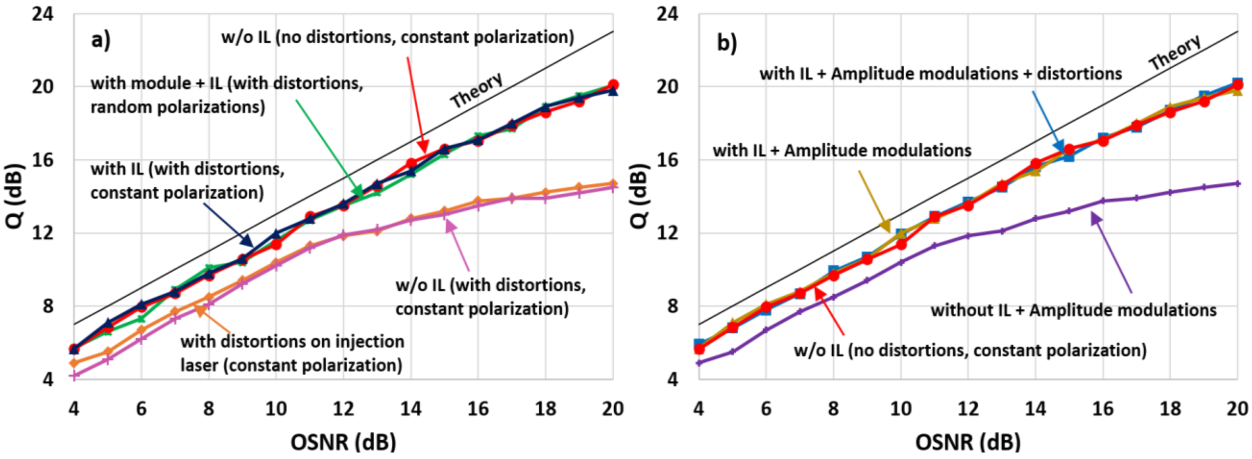

Fig. 4. *Q* performance *vs.* OSNR: a) with or without (w/o) injection locking (IL); b) Amplitude modulation with injection locking.

The third step in the proof-of-concept was to ensure that the amplitude modulation caused by the proposed module does not cause a loss of lock. This ensures that the system can remain operational when the incoming residual carrier has equal power in both horizontal and vertical polarizations, i.e. with the largest amplitude modulation. For this, the signal was amplitude modulated before passing it through the OIL setup and the performance (yellow curve in Fig. 4b) was measured which was found to give no penalty as compared with the reference (red curve in Fig. 4b). This result is because of the high rejection of low-frequency amplitude modulation by the OIL [3], which maintains injection locking even at the nulls of the incoming amplitude-modulated signal. In the case when the system does not use OIL, these amplitude modulations will pass through to the receiver and we get degradation in the performance (purple curve in Fig. 4b). With phase distortions again added into the system before the 3-dB split, the performance (blue curve in Fig. 4b) gave no penalty compared with the reference. From this we infer that OIL is able to negate the effects of distortion and amplitude modulation without losing its lock.

5. Conclusions

A pluggable module that makes an optical injection locking setup independent of the polarization of the incoming signal is proposed. The system is experimentally demonstrated and observed to give no penalty to random polarizations, phase distortions in the signal and amplitude modulations caused due to the pluggable module in comparison with the signal detected in a simple receiver without injection locking.

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6. References

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