Optical Feed-forward Carrier Recovery using Semiconductor Optical Devices and Low Frequency Electronics

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Summary
We demonstrate an innovative scheme for data-rate agnostic, wavelength-agile and real-time carrier recovery of carrier-suppressed PSK signals. Sub-Hz frequency tracking of the extracted carrier from a 21.5Gbit/s BPSK signal is demonstrated.

Introduction

Nowadays, the key coherent technology component, the heterodyne optical coherent receiver, consists of a free-running local oscillator (LO) laser, a 90° optical hybrid demodulator and balanced photodetectors. To recover the data, these system components need digital signal processing (DSP) techniques to perform phase and frequency offset estimation and correction. For operation at symbol rates of 10GBd or more, both customised, energy-hungry (20W [1]) DSP devices and free-running LOs of sufficiently narrow linewidth are needed in order to meet the stringent requirements of high level modulation formats.

The use of a photonic integrated homodyne detection scheme would relax the specification on linewidth of the LO laser and reduce the overall power dissipation by eliminating the need for the DSP used for phase offset estimation in the heterodyne detection schemes used currently [2]. However, to be practical, photonic integrated homodyne receivers require an energy-efficient method to extract an optical carrier which is phase/frequency locked to the received phase modulated signal.

Several photonic methods for carrier recovery (CR) of phase-shift keyed (PSK) signals have previously been demonstrated using either feed-back or feed-forward approaches. In several reports, optical processing in difficult-to-integrate, relatively bulky, and power demanding highly non-linear optical fibres (HNLF) is used [3], [4]. Another published approach is to use semiconductor lasers for the amplification of the residual carrier left within the signal spectrum (‘pilot tone’) by use of optical injection locking [5]. This method is modulation format independent and can be photonic integrated, however part of the available bandwidth is sacrificed due to the special coding used to minimise low frequency content in the vicinity of the transmitted pilot tone.

In this work, we present a novel implementation of the feed-forward method presented in [4]. Our implementation uses fewer components as it just requires one nonlinear process, i.e. FWM, which only takes place over a limited bandwidth: enabling a simple implementation with semiconductor optical devices only. This allows for photonic integration while reducing the required optical bandwidth and the overall power dissipation. Similarly to [6], our method recovers the carrier in real time, from a relatively fast optical phase-encoded signal using only commercially available electronics that are significantly slower than the baud rate of the data signal.

In-band Carrier Recovery Principle and Set-up

The method consists of two stages. In the first stage, the modulation is stripped off using FWM. The modulation-free optical signal, carrying the information about the carrier-frequency/phase-variations, is down-converted into the baseband. In the second stage, this down-converted signal is processed electronically and transferred back into the optical domain via optical modulation.

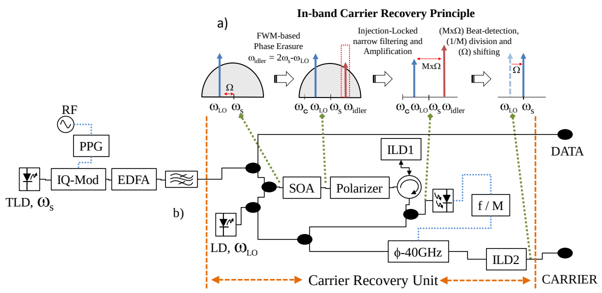

Fig. 1. Carrier recovery. a) Principle and b) Experimental setup

Fig. 1a depicts the proposed principle for binary PSK (BPSK) carrier recovery. At the input, we have the data (at frequency ω_s) and a CW-LO (at ω_{LO}) with a wavelength close to that of the carrier – the CW-LO is inside the bandwidth of the data signal. This is identical to a standard heterodyne DSP-aided coherent receiver.

First, we tap both the signal and CW-LO and combine them together at a coupler, both co-polarized. Then, we launch this combined signal into a semiconductor optical amplifier (SOA), to perform the phase erasure through FWM. We use polarization maintaining (PM) fibres and a 50/50 no-pigtail-connectorised optical PM splitters/couplers to avoid polarization fading. The FWM generates a modulation-stripped idler signal at frequency $\omega_{idler} = 2\omega_s - \omega_{LO}$ which can be written as;

$$\omega_s = (\omega_{idler} + \omega_{LO})/2 = \omega_{LO} + (\omega_{idler} - \omega_{LO})/2 \quad (1)$$

Equation (1) suggests that the modulation-stripped carrier, at its original frequency ω_s, can be obtained by shifting the CW-LO frequency by $(\omega_{idler} - \omega_{LO})/2$. The $(\omega_{idler} - \omega_{LO})/2$ can be obtained by detecting the beat between the idler and the CW-LO and dividing it subsequently by two.

The SOA output is used to injection-lock a semiconductor laser (ILD1) which performs narrow-band filtering of an idler (the choice of the idler depends on the modulation format, e.g., the first idler for BPSK, third for QPSK, etc. [6]). This idler and a portion of the original CW-LO are combined in a coupler and sent to a 12GHz photodetector to generate the beat signal $\Omega_{beat} = (\omega_{idler} - \omega_{LO}) = 2(\omega_s - \omega_{LO})$. The beat signal is processed by a digital RF divider capable of division by M (M=1,2,4,8). The value of M is chosen to match the degree of phase encoding in the data signal (e.g. M=2 for BPSK and M=4 for QPSK).

After frequency division, the obtained electrical signal is amplified and used to drive a phase modulator. The optical modulator generates harmonics at multiples of the electrical drive signal. We choose the first harmonic via optical injection locking of a laser ILD2. Therefore, shifting the frequency of the CW-LO to that of the data signal through the operation:

$$\omega_{LO} + (\Omega_{beat})/2 = \omega_{LO} + 2(\omega_s - \omega_{LO})/2 = \omega_s \quad (2)$$

Experimental Implementation and Results

The experimental setup is shown in Fig. 1b.The input signal to the CR unit is a 21.5Gbit/s BPSK signal. A tuneable laser with a measured 3dB-linewidth of 126-kHz and output power of 14.6 dBm is used as the carrier. An optical transmitter module with auto-bias control delivered the BPSK signal. At the input of the CR unit, the transmitted signal is amplified to 15 dBm and filtered using a 1nm band-pass filter. The CW-LO is a fixed-wavelength 1544.5-nm laser with 3dB-linewidth of 6-kHz amplified to 17 dBm.

To enhance the FWM efficiency and generate a stronger FWM-idler, the employed SOA is in fact a cascade of two semiconductor optical amplifiers (c-SOA). The two sections of the c-SOA were biased at 350 mA and 450mA, respectively. The c-SOA average input power was 5.8 dBm.

The electrical SNR of the beating product just after the FWM process is 21 dB with a peak power of -19 dBm (see Fig. 2c), which proved to be insufficient for the frequency division process. For this reason the c-SOA output is filtered through optical injection locking of a CSG-DR-LD's [6] semiconductor tuneable laser, emitting 15 dBm. The input signal is polarization-optimized (using a polarization controller) to filter out

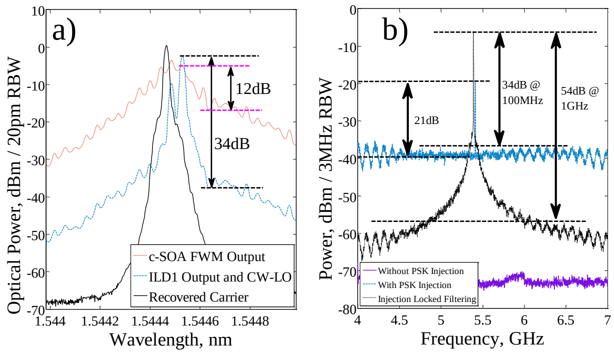

Fig. 2. SOA and ILD1 output spectra and beating signals. a) Optical, b) Electrical

the data signal. The laser bias is fine-tuned to injection-lock to the FWM-generated idler. In this way, a data rejection of 34 dB within a bandwidth of 100MHz and with a peak power of -6dBm was achieved, see Fig. 2b. Signals at the c-SOA and the ILD1 outputs are shown in Figs 2a and 2b for the optical and electrical domains, respectively.

The ILD1 output is then coupled together with a portion of the CW-LO (dashed blue line in Fig. 2a) and photodetected. The input optical power to the photodetector was 0 dBm. The beat signal, with a 40 dB SNR and 0 dBm peak power, is amplified by a 5-GHz amplifier and inserted into a digital frequency divider. The frequency divided signal is fed to a 2.5-GHz amplifier which drives a $LiNbO_3$-based phase modulator. Finally, at the output of the phase modulator, the desired harmonic is filtered out to recover the data's carrier. This is achieved using an injection-locked semiconductor laser, TDA-DR-LD [7], solid line in Fig 2a.

To qualify the recovered carrier, a static characterization (i.e. no data) was carried out. The interference pattern between the original carrier and the recovered carrier was assessed through the experimental setup shown in Fig. 3. Such a pattern drifts due to a slowly varying relative phase originating from thermal drift in the fibres (drifting on the seconds time scale). Such a drift will be negligible once the system is photonic integrated and can be easily compensated for.

A periodic pattern also appears in a different time scale, see Fig 3a. This periodic interference pattern indicates that the recovered carrier is correctly following the tuneable laser (original carrier).

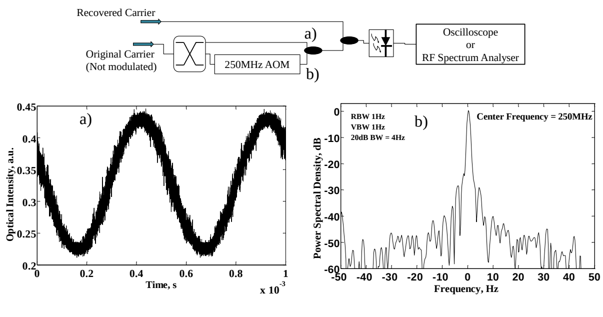

Fig. 3. Static assessment. a) Homodyning and b) Heterodyning

The electrical RF spectrum of this interference was analysed by heterodyning both signals. A 250-MHz acousto-optic modulator was introduced to shift the original carrier from DC, see Fig. 3b. The beat between the two signals is narrower than 1 Hz which is the resolution limit of our RF spectrum analyser. A 20dB BW at 4Hz was measured, most probably also limited by the instruments.

Following the static characterization, we tested the CR unit using BPSK modulated data. The homodyne detected constellation obtained for a 21.5Gbit/s signal (real-time oscilloscope limit) is shown in Fig. 4b. Data was recovered without the use of any intermediate frequency with rms-EVM values ranging between 15% and 19%.

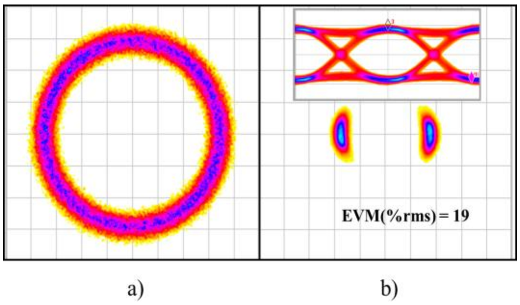

Fig.4. 21.5Gbit/s Homodyne constellation plots. a) Un-locked CR unit, b) Locked CR unit

Conclusions

We present an innovative wavelength-agile, data-rate agnostic, and real-time CR unit for PSK signals which uses uniquely Indium Phosphide devices for optical signal processing and is capable of recovering the carrier at its original frequency with <1 Hz precision. It uses a single ultra-fast FWM process together with low-frequency electronics to reduce the required optical bandwidth, cost and system complexity. Narrowband optical filtering using injection-locked tuneable semiconductor lasers enables full tunability (e.g., across the C-band).

The demonstrated CR unit represents a step change towards future energy-efficient tuneable photonic integrated homodyne transceivers for metro/access and coherent data-centre applications.

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