Feed-forward true carrier extraction of high baud rate phase shift keyed signals using photonic modulation stripping and low-bandwidth electronics

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Abstract: Retrieving the full information carried by phase shift keyed (PSK) data streams requires a reference local oscillator (LO). If the receiver utilizes digital signal processing (DSP), a free-running LO can be used, although several benefits can be derived from generating an optical LO that is locked in frequency and phase to the original signal carrier (which is unfortunately suppressed in the PSK data modulation process). Here, we present a new concept of carrier recovery. Using nonlinear optics, we strip the data modulation and derive an error signal proportional to the phase/frequency difference between a free running intradyne LO and the data-stripped signal. After extracting this frequency difference (using slow electronics), we frequency shift the free running LO by this amount, effectively obtaining a homodyne LO. The carrier is recovered to a precision of better than ±0.5 Hz and the method is tested by performing homodyne detection of a 20 Gbaud binary PSK signal.

OCIS codes: (060.1660) Coherent communications; (070.4340) Nonlinear optical signal processing.

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1. Introduction

Current high speed optical coherent receivers use intra or hetero-dyne coherent detection aided by DSP to retrieve a reference carrier for phase demodulation of carrier-suppressed PSK signals [1]. However, for many applications, it may be advantageous, and in certain cases a requirement, to recover the signal carrier directly in the optical domain. For example, for homodyne all-optical regeneration, a reference local oscillator (LO) must be synthesized locally. Another example is the afore-mentioned coherent detection, in which it may be

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advantageous to pre-process the signal optically (e.g., to demultiplex it) and/or to perform homodyne coherent detection to reduce the electronic DSP processing demands. The urgent need for carrier extraction is evidenced by recent reports in the literature of several novel carrier recovery schemes [2–4]. Generally, feed-back [2] or feed-forward methods [3] are used. Alternatively, the carrier can be transmitted in a separate polarization or frequency channel to the signal, or the data coding may be modified to leave some residual component of the carrier in the data spectrum [4]. The feedback methods require short loop delays to achieve reasonable (> MHz) bandwidths, something that is ultimately limited by the physical layout of electronic and optical devices. The published feed-forward schemes are limited to processing signals with bandwidths less than that of electronics (e.g., in [3], 10 Gbaud signals are processed with >10 GHz electronics).

Here, we present a novel method that is based on a feed-forward configuration and which generally requires electronics that is slower than the baud rate of the data signal. It consists of two stages. In the first stage, ultrafast four wave mixing (FWM) is used to down-convert the carrier variations to the baseband (<10 GHz). In the second stage, the carrier variations are processed electronically and transferred back into the optical domain via optical modulation.

2. Principle of the proposed method

As suggested above, we start with an Intradyne LO and 'measure' the instantaneous frequency difference between the Intradyne LO and the data carrier. Subsequently, we shift the Intradyne LO by this amount, obtaining a Homodyne LO (LO perfectly locked to the data carrier). To measure the instantaneous frequency difference with slow electronics, we first need to strip the (fast) data modulation off the incident data stream [5].

Modulation stripping [5] can in principle handle phase-encoded signal (PSK) of an arbitrary number of levels. For the sake of simplicity, we demonstrate it on binary PSK (BPSK) and quadruple PSK (QPSK), however from this extension to an arbitrary number of levels is straightforward to understand. First, the incident data signal is mixed via FWM with a continuous wave (CW) pump in a non-linear medium (e.g., a highly non-linear optical fiber, HNLF). For BPSK modulated data, momentum conservation requires that the first idler (Fig. 1) has phase:

$$\varphi_{idler}^{1} = 2\left(\varphi_{data}^{BPSK} - \varphi_{carrier}\right) - \varphi_{pump} = 2\varphi_{data}^{BPSK} - 2\varphi_{carrier} - \varphi_{pump}. \tag{1}$$

Because $\varphi_{data}^{BPSK} = 0, \pi$, we get $2\varphi_{data}^{BPSK} = 0, 2\pi \equiv 0$ meaning that $2\varphi_{data}^{BPSK}$ is zero for all bits - either carrying logical '0' ($\varphi_{data}^{BPSK} = 0$) or logical '1' ($\varphi_{data}^{BPSK} = \pi$). Thus, putting $2\varphi_{data}^{BPSK} = 0$ into Eq. (1), we get an idler with the modulation stripped off:

$$\varphi_{idler}^{1} = -2\varphi_{carrier} - \varphi_{pump}. \tag{2}$$

For QPSK, we need to consider cascaded FWM processes, in which the generated idlers interact with the original pump and data signals producing higher-order idlers. In QPSK, data is encoded using four logical levels $\varphi_{data}^{QPSK} = 0, \pi/2, \pi, 3\pi/2$ and it is the third idler that contains the modulation-stripped term $4\varphi_{data}^{QPSK} = 0, 2\pi, 4\pi, 6\pi \equiv 0$ (Fig. 1) [6]:

$$\varphi_{idler}^{3} = 4\left(\varphi_{data}^{QPSK} - \varphi_{carrier}\right) - \varphi_{pump} = -4\varphi_{carrier} - \varphi_{pump}. \tag{3}$$

It can easily be seen that for an M-level PSK, the (M-1)st idler is modulation stripped.

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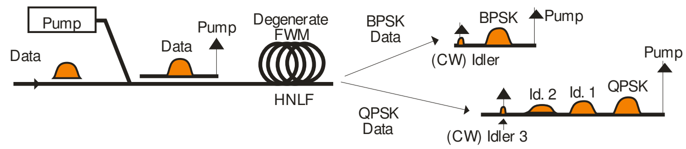

Fig. 1. Modulation stripping – principle shown for the example of BPSK and QPSK modulation formats.

Although the idlers of interest (e.g., 1st for BPSK and 3rd for QPSK) are data modulation free, they are not utilizable as a homodyne LO for the following reasons. First, they possess phase fluctuations originating from the pump laser which itself has a finite linewidth. Secondly, the idler wave does not follow the signal carrier itself, but its (M-1)th multiple. Finally, the idler wave is at different wavelength, which is undesirable for most applications (e.g., it cannot be used for homodyne detection).

Our method includes further steps to mitigate all the three above-mentioned issues. For the sake of simplicity, we will explain it in the context of BPSK modulated signals, however again from this extension to higher modulation formats is straightforward.

First, we perform the modulation stripping as described above; however in parallel we perform a second FWM mixing process between a second CW signal (Intradyne LO) with a component of the same Pump. The Intradyne LO has its wavelength reasonably close to that of the data carrier (e.g. <10 GHz away). The criteria by which we define 'reasonably close' will become clear later. The frequency difference between the Intradyne LO and the data carrier is denoted as $\Omega_{beat}/2$ in Fig. 2. The modulation stripping produces an idler denoted as 'Idler', while the second FWM process produces another idler denoted as 'LO Idler' in Fig. 2.

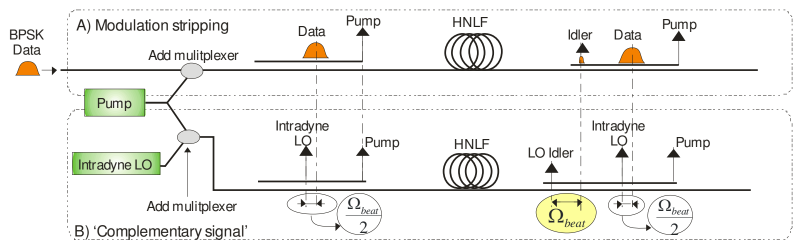

Fig. 2. First step of the proposed method: Modulation stripping (a) is performed simultaneously to a similar process in which the data signal is replaced by an Intradyne LO (b).

Mathematically, this first stage generates two idlers with frequencies given by:

$$\omega_{idler} = 2\omega_{carrier} - \omega_{pump} ; \omega_{LOidler} = 2\omega_{intradyneLO} - \omega_{pump} \quad (4)$$

Subsequently, we filter the two idlers and beat them together at a photodetector, Fig. 3, obtaining radio frequency (RF) beating of the two idlers at frequency Ω_{beat} that is twice that of the frequency difference between the Intradyne LO and the data carrier, see Fig. 2, as follows from the basic frequency matching condition of the FWM.

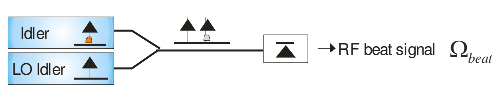

Fig. 3. Beating of the two idlers at a photodetector produces a beat signal at Ω_{beat} .

Using Eq. (4) we obtain:

$$\Omega_{beat} = \omega_{idler} - \omega_{LOidler} = 2\omega_{carrier} - 2\omega_{intradyneLO} \quad (5)$$

which does no longer depends on the Pump frequency. Considering the RF beat frequency Ω_{beat} can readily be divided by two, we get:

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$$\omega_{carrier} = \Omega_{beat}/2 + \omega_{intradyneLO}. \quad (6)$$

Thus, the carrier (Homodyne LO) can be straightforwardly obtained by shifting the Intradyne LO frequency by RF frequency $\Omega_{beat}/2$. This could be done using an acousto-optic modulator, single-sideband modulator, or a standard phase modulator followed by narrow band filtering of the modulation sideband (e.g., by injection locking of a semiconductor laser), see Fig. 4. Frequency division at 10-GHz speeds can be easily carried out using a digital RF frequency divider. Now, we can understand what we mean by the term 'reasonably close' - Ω_{beat} needs to be sufficiently small to be detectable by a photodetector and the frequency shifter needs to be able to apply a shift of $\Omega_{beat}/2$. On the other hand, it must be big enough to ensure that the difference between the Intradyne LO and data carrier is always positive or always negative, as the beat detector in Fig. 3 can detect only the magnitude of Ω_{beat} and not its sign. A key feature is that the data modulation speed does not impose any limit on Ω_{beat} meaning that very high baud rates can be processed despite Ω_{beat} being relatively small.

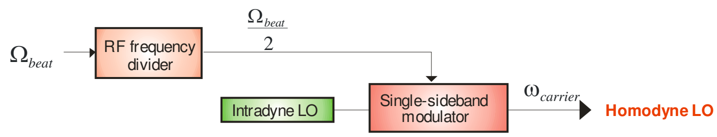

Fig. 4. Carrier recovery using RF frequency divider and a single-sideband modulator as an example of an optical frequency shifter.

In currently installed telecom systems, the data carrier can fluctuate up to by ± 1GHz and the above conditions thus dictate $\Omega_{beat} > 4\ GHz$. Using a digital frequency divider with 12 GHz bandwidth and a single-sideband modulator with 6-GHz bandwidth, we would get 6 GHz > $\Omega_{beat} > 4\ GHz$. However, lower bandwith processing should be possible simply by actively controlling the Intradyne LO frequency so that it tracks the slowly drifting data carrier frequency in which case the minimum bandwidth limitation would be determined by the linewidths of the carrier and the Intradyne LO lasers. Assuming a practical value of 1 MHz for the two laser linewidths, electronics operating in the hundreds of MHz range should be more than sufficient in this instance.

The method can easily be extended to higher modulation formats by using frequency division by M, which can be done with commercially-available digital frequency dividers.

3. Set-up

We tested the method with BPSK data modulation. For a practical implementation, several details had to be addressed to allow efficient operation of the method. First, the two FWM processes cannot be performed simultaneously (same fiber, same polarization, same propagation direction), as the FWM product of 'Pump + Intradyne LO + Data' that carries the original data would be generated in the same frequency region as the two idlers of interest. Performing these two FWM processes in two different HNLF would, however, lead to different phase variations of the two generated idlers as a result of the different acoustic pick-up in the two HNLFs, which would generate phase variations in the (sub)kHz regime (where acoustic waves are present). To avoid this, we used the same HNLF, but operated it bi-directionally with Pump + Intradyne LO launched from the opposite side with respect to the Pump + Data. Another issue to address originates from the fact that Idler generated from the Data signal has strong amplitude variations due to the amplitude variations of the Data stream, as the Data signal was generated using an amplitude modulator (symmetrically driven around the null point). This strongly disrupts the frequency division process. To eliminate such problems we performed amplitude regeneration of the idler [3] via injection locking of a semiconductor laser (Eblana Photonics, Inc, Ireland). An alternative option would be to perform balanced detection. The set-up built is shown in detail in Fig. 5 with some key optical/RF spectral characteristics shown in Fig. 6.

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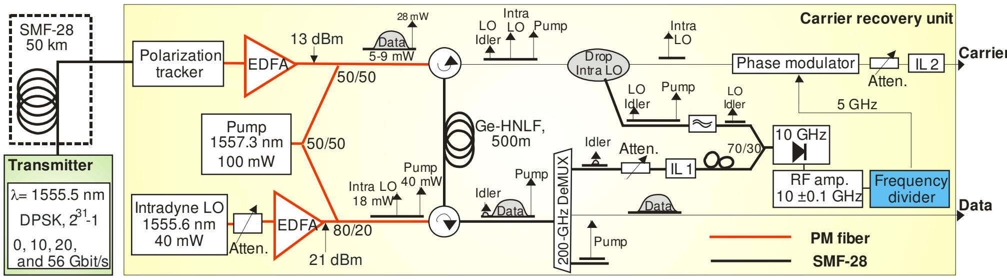

Fig. 5. Set-up of the realized carrier recovery scheme. IL – injection –locked laser, BPF – band pass filter, DeMUX – demultiplexer, EDFA – Erbium-doped fiber amplifier.

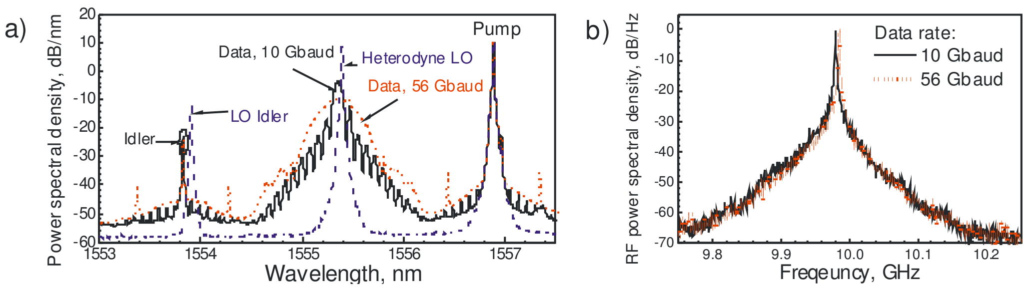

Fig. 6. (a) Spectra measured at the output of the Ge-HNLF for 10 Gbaud (black solid) and 56 Gbaud (red dotted) data rates together with the 'complementary signal' spectra (blue dash). (b) RF spectrum of the detected beat signal at 10 GHz obtained for 10 Gbaud (black solid) and 56 Gbauds (red dotted) data rates, respectively.

4. Results

First, we switched off the data modulator and characterized how the free running CW laser (Intradyne LO) could be phase synchronized with the input optical wave (200 kHz linewidth laser, Eblana Photonics, Ireland). For this characterization, we observed the interference pattern between the original input signal and the output signal of the carrier recovery unit, Fig. 7a. Here, we clearly see that the two signals interfere with slowly varying relative phase (on a time scale of seconds) due to thermal drift in the fibers. This experiment was further complemented by analyzing the RF spectrum of this interference (to shift it from zero frequency, a 140-kHz phase dither was introduced at the input of the original signal), Fig. 7b. Here, we see that the beat between the two signals is narrower than 1 Hz (resolution limited by our RF spectrum analyzer) confirming the previous result that the carrier was recovered to better than 1 Hz precision (more than five orders of magnitude below the natural linewidth of the data laser).

Following the static characterization, we tested the set-up using BPSK modulated data at various data rates (up to 56 Gbaud) - both straight from the transmitter and also in the presence of high residual dispersion (corresponding to 50 km of SMF-28 fiber). By monitoring the optical and electrical spectra at various points in the set-up we confirmed that the scheme worked properly (e.g., the digital frequency divider had sufficient signal and signal-to-noise ratio to operate properly, the two slave lasers were reliably injection-locked, etc.). Following these checks, we performed homodyne detection at 20 Gbaud(limited in speed by our real time oscilloscope). Constellation diagrams were plotted without any intermediate frequency or phase-error estimation; the only electronic post-processing was digital dispersion compensation. The results are shown in Fig. 8a and Fig. 8b. Here, we see that the data was fully recovered with no intermediate frequency present, even after 50 km of SMF-28 dispersive propagation (equivalent effect to 200 km for 10 Gbaud data). For comparison, the constellation obtained with a narrow-linewidth (kHz- range) free running LO tuned carefully to obtain a low intermediate frequency is also shown in Fig. 8c.

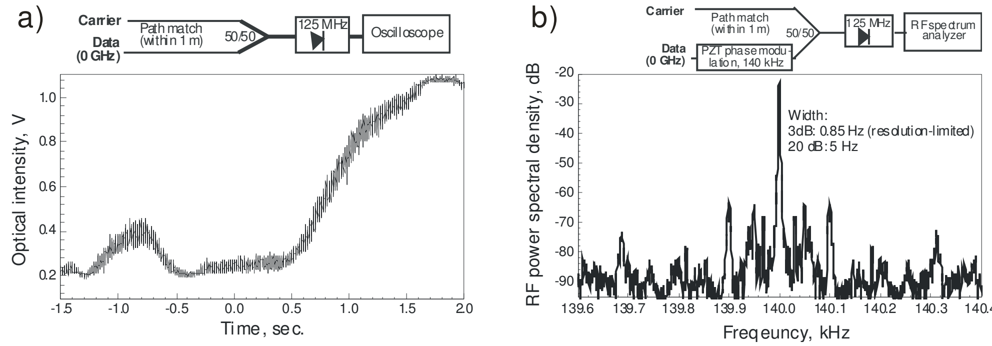

Fig. 7. Set-up (upper panels) and results (lower panels) of the static measurement - homodyne in temporal domain (a) and heterodyne in the RF frequency domain (b).

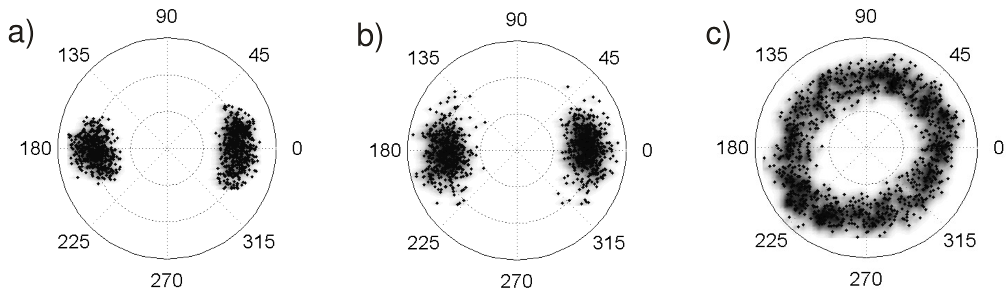

Fig. 8. Homodyne constellation plots for a 20 Gbaud stream with (a) no dispersive propagation, (b) after propagation through 50 km of SMF-28 with effects of dispersion removed by digital signal processing (b). For comparison, the constellation obtained with a free running LO is also shown (c).

5. Conclusions

We present and demonstrate a novel scheme for carrier recovery of phase-encoded signals capable of recovering the carrier at its original frequency with a precision better than 1 Hz. The processing bandwidth is virtually unlimited as it is based on an ultrafast FWM process. In our demonstration, the carrier frequency of a semiconductor laser with a linewidth of 200 kHz is successfully recovered. We show results for 20 Gbaud rate being limited only by our homodyne receiver. We also demonstrated the ability to recover the carrier from data significantly impaired by dispersion - data transmitted through 50 km of SMF-28 fiber at 20 Gbaud. The scheme can be straightforwardly modified to enable carrier recovery from higher modulation format signals, e.g., QPSK.

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