Feed-forward True Carrier Extraction of High Baud Rate PSK Signals Using Slow Electronics

Radan Slavík, Joseph Kakande, and Dave J. Richardson
Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1 BJ, United Kingdom
Author e-mail address: r.slavik@soton.ac.uk

Abstract: Novel principle based on four-wave mixing and intra-band RF frequency division with self-compensation of the pumps frequency noise is introduced. Homodyne detection of 20Gbit/s BPSK data is performed using RF electronics limited to 10GHz.
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1. Introduction

Today's mainstream towards coherent signal processing is based on intra or hetero-dyne coherent detection with subsequent digital signal processing that has to remove the intermediate (intra/hetero-dyne) frequency first [1]. Thus, to process a signal, it must be inevitably converted into the electronics domain. However, for many applications, it might be advantageous to process the signal directly in the optical domain, in which case the carrier phase locked to the data may be necessary. For example, for optical regeneration, the input and output signals are preferably in optical domain. Another example is above-mentioned coherent detection, in which it may be advantageous to pre-process the signal optically (e.g., demultiplex it) and/or perform homodyne coherent detection to reduce the load imposed on the electronics digital signal processing stage. The emergency of need for carrier extraction is witnessed by several novel schemes published recently [2]-[4]. Generally, a feed-back [2] or feed-forward methods [3] are used. Alternatively, the carrier can be transmitted as a separate signal or the data coding may be modified to give presence of the residual carrier in the data spectrum [4]. The feedback methods lack speed which is limited by delay in the feedback loop. The published feed-forward schemes are limited to processing signals with bandwidths less than that of electronics (e.g., in [3], 10 GHz signals are processed with >10 GHz electronics).

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

2. Principle of the proposed method

The operational principle of the first stage that contains two FWM processes is schematically shown in Fig. 1. Here, we have two *pumps* and *data* signal. The *pump1* frequency lies outside the bandwidth of the *data* signal, while the *pump 2* frequency is within several GHz from the expected *data* carrier frequency. Due to FWM, there are two *idlers* of interest, as shown in Fig. 1. For the two *idler* frequencies, we write:

$$\omega_{idler1} = 2\omega_{data} - \omega_{pump1};\ \omega_{idler2} = 2\omega_{Pump2} - \omega_{pump1}\ . \tag{1}$$

Filtering the two idlers and beating them together at the detector leads to RF frequency

$$\Omega_{Beat} = \omega_{idler1} - \omega_{idler12} = 2\omega_{data} - 2\omega_{pump2}\,, \tag{2}$$

which does not depend on *pump 1* any more. Considering the RF beat frequency can be divided by two, we get:

$$\omega_{data} = \omega_{pump2} + \Omega_{Beat}/2\,. \tag{3}$$

Thus, the carrier can be obtained by shifting the *pump 2* frequency by RF frequency $\Omega_{Beat}/2$. This could be done in an acousto-optics modulator, single-sideband modulator, or a standard phase modulator followed by narrow band filtering of the modulation sideband (e.g., by injection locking).

The method can be easily broadened to higher modulation formats having *N* phase levels by using higher FWM products (*N-1*th one) [5] and frequency division by *N*.

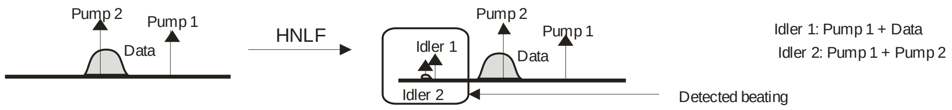

Fig. 1 FWM preprocessing - principle of operation.

3. Set-up

In 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, as the FWM product of *pump 1* + *pump 2* + *data* that carries 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 different acoustic pick-up in the two HNLFs, which would generate phase variations in the (sub)kHz regime (where acoustics waves are present). To avoid it, we used the same HNLF, but operated it bi-directionally with *pump 1* + *pump 2* launched from the opposite side in respect to *pump1* + *data*. Another aspect to address originates in the fact that *idler 1* generated from the *data* signal has strong amplitude variations originating in the amplitude variations of the *data* stream, as *data* were generated using an amplitude modulator (symmetrically driven around zero transmission). This would bring a strong error into the frequency division process. Thus, we injection locked a semiconductor laser (Eblana Photonics, Inc, Ireland) by *idler 1* that allows for great amplitude regeneration [3] of it. The built set-up is shown in Fig. 2.

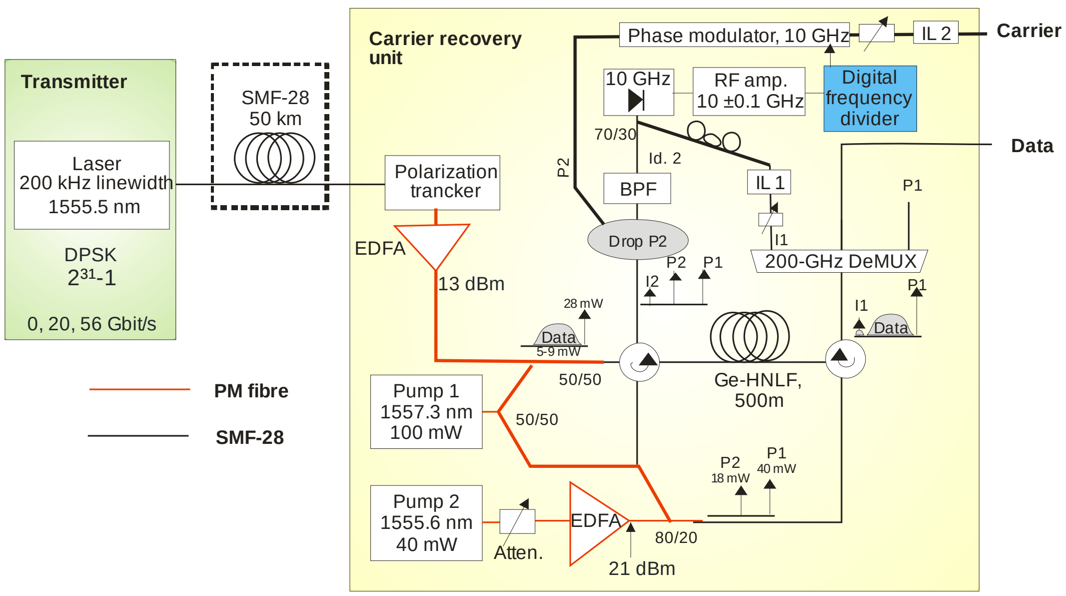

Fig. 2 Set-up of the realized carrier recovery scheme.

First, we switch off the data modulator and characterized how the free running cw laser (*pump 2*) can be phase synchronized with the input optical wave (200 kHz linewidth laser). For this characterization, we observed the interference pattern between the original input signal and the output signal of the carrier recovery unit, Fig. 3a. Here, we clearly see that the two signals are interfering together with slowly varying relative phase (at time scale of seconds) due to thermal drift in the fibres. 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 input of the original signal), Fig. 3b. Here, we see that the beating 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 magnitudes 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 Gbit/s) both straight from the transmitter and also in the presence of high residual dispersion corresponding to 50 km of SMF-28 fibre. The obtained unprocessed constellation diagrams (only with 50-km dispersion removed in software) for 20 Gbit/s (speed limited by our RF real time oscilloscope) are shown in Fig. 4a and Fig. 4b. Here, we see that the data were fully recovered with no intermediate frequency present, even after 50 km of SMF-28 dispersive propagation (equivalent effect to 2000 km on 10 Gbit/s data).

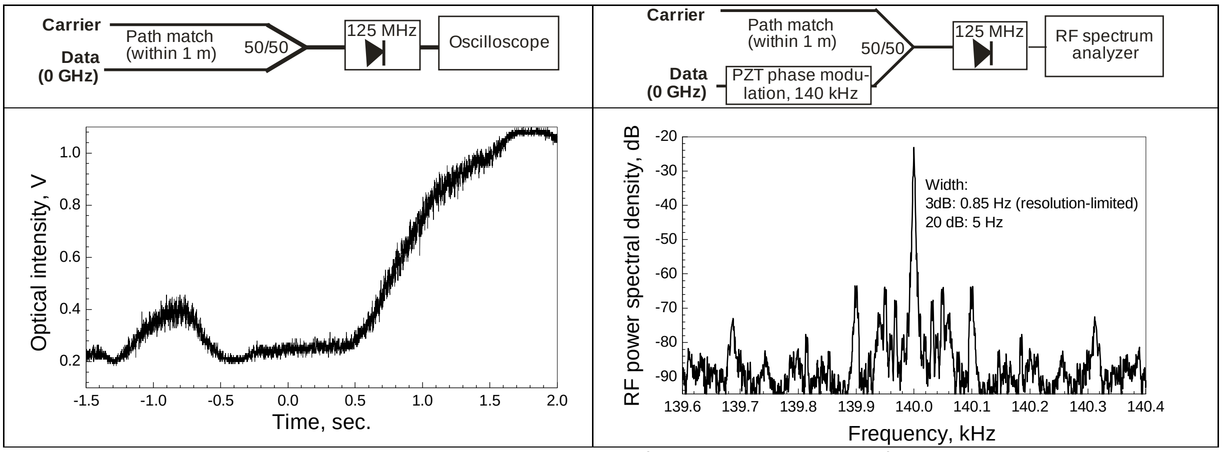

Fig. 3 Static measurement - homodyne in temporal domain (left) and heterodyne in the RF frequency domain (right).

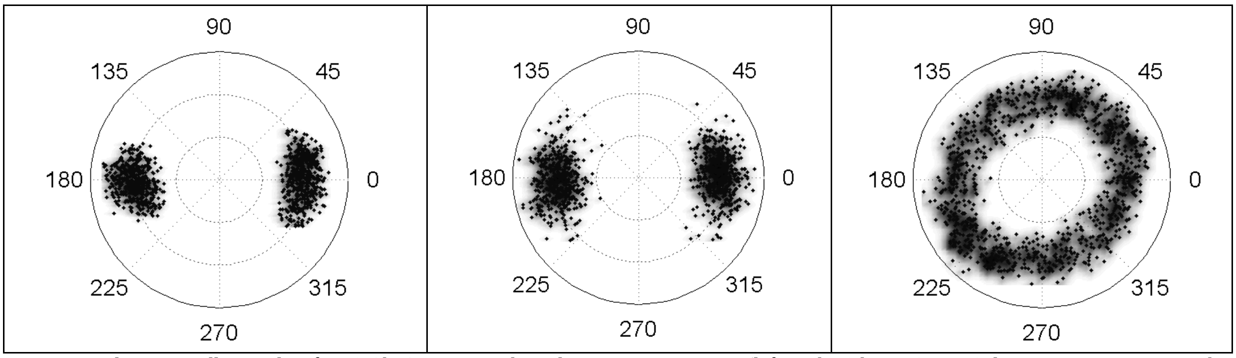

Fig. 4 Homodyne constellation plots for 20 Gbit/s stream with no dispersive propagation (left, with 50 km in SMF-28 dispersive propagation with dispersion effect removed in software (middle). For comparison, the constellation obtained with free running local oscillator is also shown (right).

4. Conclusions

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

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5. References

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