Optical carrier extraction from carrier-less phase modulated optical signals

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Abstract: We propose a novel and simple carrier recovery method from carrier-less phase modulated optical signals. In this method, homodyne detection of the received signal, modulation stripping by an electro-optic phase modulator, and injection locking of a laser diode for carrier generation are performed in a feedback loop. Carrier extraction and error-free homodyne detection of a 10-Gb/s RZ-BPSK signal is demonstrated. The method can also be extended to carrier extraction from QPSK signals.

Keywords: homodyne detection, injection locking, phase modulation
Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Carrier extraction from data-modulated optical signals is an important task in homodyne detection systems [1]. Although post-detection carrier phase estimation in the digital domain using a free-running local oscillator (LO) is widely favored in current coherent transmission systems [2], the original approach to homodyne detection using a carrier-phase synchronized LO still has advantages such as potentials of lower-power consumption and compact receiver structures. The optical carrier extraction is also needed in coherent signal processing such as phase-sensitive amplification [3]. Because carrier is suppressed in most of practical modulation formats used in coherent systems such as binary or quaternary phase shift keying (BPSK or QPSK) and quadrature amplitude modulation (QAM), extraction of carrier from such carrier-less signals is particularly important. In addition to the Costas-loop scheme [4, 5] traditionally used in wireless systems, several schemes of optical carrier extraction from carrier-suppressed signals have been recently proposed. In [6], all-optical carrier extraction by a fiber-based phase sensitive oscillator pumped by amplified BPSK signals was demonstrated. In [7], feed-forward carrier extraction using opto-electro-optical modulation stripping together with injection locking of a laser diode (LD) was proposed. Low-speed electrical signal processing combined with all-optical modulation stripping by the parametric process in a nonlinear fiber was used for carrier extraction from high baud rate PSK signals in [8].

We have proposed another approach for the carrier extraction from carrier-less BPSK and QPSK signals, where homodyne detection, modulation stripping by an electro-optic modulator, and injection locking of a LD are performed in a feedback loop [9, 10]. This approach requires neither high-speed electrical signal processing used in the Costas-loop method [4, 5] and in [7] nor large optical powers that are needed in the all-optical methods. In this Letter we describe the principles and details of the proposed carrier extraction method.

2 Carrier extraction from BPSK signals

2.1 Principle of carrier extraction

Fig. 1 shows a schematic of the proposed carrier extraction circuit. A part of the incoming BPSK signal is coherently detected with a LO light provided by an injection-locked laser diode (ILLD). The detected electrical signal drives an electro-optic phase modulator (PM) in which the phase of the other part of the incoming BPSK signal is modulated. Here we denote the signal and LO phases as $\theta_s$ and $\theta_{LO}$. Fig. 1. Schematic of the BPSK carrier extraction circuit.
respectively. The amount of phase modulation is then given by
\[ k \cos(\theta_k - \theta_{LO}) \]
where \( k \) is determined by the signal and LO power, responsivity of the detector, gain of the driver amplifier, and the modulator \( V_x \). When the path lengths of the optical and the driving electrical signals are matched so that the optical signal is phase-modulated by its own data, the complex amplitude of the signal after the modulator is given by
\[ E_1(\theta_s, \theta_{LO}) = A \exp(i\theta_k) \exp[ik \cos(\theta_k - \theta_{LO})], \]  
(1)
where \( A \) is an amplitude and \( \theta_k \) takes value either 0 or \( \pi \). When \( \theta_{LO} = 0 \) is assumed and \( k \) is chosen to be \( \pi/2 \), the phase modulation is totally erased so that the carrier is recovered. The recovered carrier is injected to the ILLD through a circulator. If the ILLD is locked to the recovered carrier, the LO light frequency- and phase-locked to the received signal is generated. When the signal phase \( \theta_k \) takes 0 or \( \pi \) with an equal probability, the carrier power after the phase modulation becomes proportional to
\[ P_{1,BPSK}(\theta_{LO}) = |E_1(0, \theta_{LO}) + E_1(\pi, \theta_{LO})|^2 = 4A^2 \sin^2(k \cos \theta_{LO}). \]  
(2)

It is found from (2) that \( P_{1,BPSK} \) takes a peak value at \( \theta_{LO} = 0 \) when \( k \) is equal to or smaller than \( \pi/2 \). Fig. 2 shows \( P_{1,BPSK} \) versus \( \theta_{LO} \) for different values of \( k \). When \( k \) is larger than \( \pi/2 \), \( P_{1,BPSK} \) takes maxima symmetrically located about \( \theta_{LO} = 0 \). The behavior of \( P_{1,BPSK} \) as a function of \( \theta_{LO} \) indicates that \( P_{1,BPSK} \) can be used as a monitor signal for the phase locking of the LO light to the carrier. By controlling \( \theta_{LO} \) so that the carrier power after the phase modulator is maximized with \( k \) set at \( \pi/2 \), the modulation-stripped carrier is injected to the ILLD and phase-locked LO light is generated.

The regeneration of carrier power is also evaluated numerically. A return-to-zero (RZ) BPSK signal having a random bit pattern is prepared. The duty ratio of the RZ pulses is 50 percent and the pattern length is 8192 bits in this simulation. The signal, complex amplitude of which is denoted as \( f(t) \), is phase-modulated by an amount in proportion to its homodyne-detected signal waveform. The complex amplitude after the phase modulation is given by
\[ f(t) \exp\{ik' \text{Re}[f(t) \exp(-i\theta_{LO})]\}, \]  
(3)
where $k'$ multiplied by the peak value of $|f(t)|$ represents $k$ in (1). The direct-current (DC) component in the spectrum of (3) gives the regenerated carrier power by the phase remodulation. The numerically calculated carrier power as a function of $\theta_{LO}$ for $k = \pi/2$ is shown by dots in Fig. 2. The power is normalized so that its peak value at $\theta_{LO} = 0$ is the same as that evaluated by (2). The numerically evaluated carrier power agrees well with that obtained analytically. Small differences in power for $\theta_{LO}$ close to $\pm \pi/2$ is caused by the fact that the phase remodulation is not constant in each bit slot due to the RZ pulse shaping so that the phase-data erasure is incomplete in the numerical simulation.

### 2.2 Experiment

![Fig. 3. Experimental setup of the BPSK carrier extraction. DL: variable delay line, PM: phase modulator, FIL: narrow-band optical filter, PC: polarization controller, ILLD: injection-locked laser diode, FS: fiber stretcher, PI: proportional and integration controller, and LIA: lock-in amplifier.](image)

Fig. 3 shows the experimental setup of carrier extraction from BPSK signals. The wavelength and linewidth of the source laser are 1555.9 nm and $\sim$12 kHz, respectively. The data rate is 10 Gb/s and the BPSK signal is carved into RZ pulses with 50 percent duty ratio. Polarization of the input signal is aligned to the axis of the LiNbO$_3$ phase modulator (PM). A variable delay line inserted in the signal path is adjusted so that the optical signal delay from the coupler to the PM is matched to the delay of the detected data reaching the driving port of the PM within a few picoseconds. A delay interferometer with a time delay of 100 ps is used as a narrowband filter that monitors the carrier power after the phase modulator. The LO phase is dithered at 24 kHz using a fiber stretcher and the frequency component at 24 kHz in the extracted carrier power is synchronously detected by a lock-in amplifier (LIA). The LO phase is controlled so that the LIA output becomes zero or the carrier power becomes maximum.

Fig. 4(a) and (b) show the optical spectra of the unmodulated RZ pulse train and the RZ-BPSK signal modulated with a pseudo-random bit stream of a pattern length $2^{31}$-1, respectively. Fig. 4(c) shows the spectrum of data-stripped RZ pulse train measured at point A in Fig. 3. Although the data erasure is not perfect, i.e. the spectra shown in Fig. 4(a) and (c) are not identical to one another, carrier component is well recovered. The radio-frequency (RF) beat spectrum between the generated LO light after the ILLD and the source light used in the transmitter is shown in Fig. 5. Lengths of the two paths are matched and an acousto-optic
modulator inserted in the source light path shifts the beat spectrum by 80 MHz. Fig. 5 shows that the beat is narrower than a few Hz limited by the resolution of the RF spectrum analyzer, which indicates that a high fidelity carrier is extracted. Fig. 6 is an eye pattern observed at point B in Fig. 3, where no error is detected for more than a few tens of seconds.

Although the experiment is reported for the RZ-BPSK format, we have confirmed that the carrier extraction scheme works also for non-return to zero (NRZ) BPSK signals.

Fig. 4. Optical spectra. (a) RZ pulse train before BPSK modulation, (b) RZ-BPSK signal, and (c) phase-erased RZ-BPSK signal. Wavelength resolution is 0.01 nm.

Fig. 5. Beat spectrum between the generated LO light and the source light. Horizontal axis: 100Hz/div, Vertical axis: 10 dB/div

Fig. 6. Eye pattern of the detected 10 Gb/s RZ-BPSK signal.
3 Carrier extraction from QPSK signals

The carrier extraction scheme described in the previous section can be extended to carrier extraction from carrier-less QPSK signals. We first consider that a QPSK signal is input to the same circuit as shown in Fig. 1. When the signal phase $\theta_s$ takes 0, $\pi/2$, $\pi$, and $3\pi/2$ with an equal probability, the carrier power after the phase modulator is proportional to

$$P_{1,QPSK}(\theta_{LO}) = |E_1(0, \theta_{LO}) + E_1(\pi/2, \theta_{LO}) + E_1(\pi, \theta_{LO}) + E_1(3\pi/2, \theta_{LO})|^2$$

$$= 4A^2[\sin^2(k \cos \theta_{LO}) + \sin^2(k \sin \theta_{LO})].$$

(4)

When $k$ is equal to or smaller than $\pi$, $P_{1,QPSK}$ takes a maximum value at $\theta_{LO} = \pm \pi/4$ as shown in Fig. 7. It, therefore, may be expected that we can achieve desirable phase locking between the LO light and the signal carrier by controlling the LO phase so that the carrier power after the phase remodulation becomes maximum. In this case, however, the phases of $E_1(0, \theta_{LO})$, $E_1(\pi/2, \theta_{LO})$, $E_1(\pi, \theta_{LO})$, and $E_1(3\pi/2, \theta_{LO})$ do not take the same value even when $P_{1,QPSK}$ is maximized at $\theta_{LO} = \pm \pi/4$. A large modulation-induced noise is still contained in the signal after the phase remodulation, which will make the injection locking unsuccessful. Fig. 8 shows numerically calculated spectra of (a) an unmodulated 10-GHz RZ pulse train with duty ratio of 50%, (b) a 10-Gbaud RZ-QPSK signal with a pattern length of 8192 symbols, and (c) the RZ-QPSK signal after the phase remodulation by the circuit shown in Fig. 1. The phase remodulation is modeled by (3) with $k$ equal to $\pi/\sqrt{2}$ and $\theta_{LO} = \pi/4$. $f(t)$ in (3) is now the RZ-QPSK signal. Fig. 8(c) shows that although the phase remodulation partially recovers the carrier, data modulation still remains in the signal.

We then use a carrier extraction circuit as shown in Fig. 9, where the phase remodulation is performed by a dual-electrode Mach-Zehnder modulator (MZM) driven by the homodyne-detected data in proportion to $\cos(\theta_s - \theta_{LO})$ and $\sin(\theta_s - \theta_{LO})$. The phase remodulated signal after the MZM is given by

$$E_2(\theta_s, \theta_{LO}) = A \exp(i\theta_s) \{\exp[ik \cos(\theta_s - \theta_{LO})] - i \exp[ik \sin(\theta_s - \theta_{LO})]\}/2,$$

(5)

where $k$ is again a proportional factor as in the BPSK carrier extraction. It is noted that $\pi/2$ phase difference is given between the two arms of the MZM. The carrier power after the MZM is proportional to

$$P_{2,QPSK}(\theta_{LO}) = |E_2(0, \theta_{LO}) + E_2(\pi/2, \theta_{LO}) + E_2(\pi, \theta_{LO}) + E_2(3\pi/2, \theta_{LO})|^2$$

$$= 4A^2[\sin^2(k \cos \theta_{LO}) + \sin^2(k \sin \theta_{LO})],$$

(6)

which is the same as (4) with $k = \pi/\sqrt{2}$.
\begin{align}
P_{2,\text{QPSK}}(\theta_{1,\text{LO}}) &= |E_2(0, \theta_{1,\text{LO}}) + E_2(\pi/2, \theta_{1,\text{LO}}) + E_2(\pi, \theta_{1,\text{LO}}) + E_2(3\pi/2, \theta_{1,\text{LO}})|^2 \\
&= 4A^2[\sin^2(k \cos \theta_{1,\text{LO}}) + \sin^2(k \sin \theta_{1,\text{LO}})],
\end{align}

which is the same as \(P_{1,\text{QPSK}}(\theta_{1,\text{LO}})\) given by (4). In this case with \(k\) equal to \(\pi/\sqrt{2}\), the phases of \(E_2(0, \theta_{1,\text{LO}}), E_2(\pi/2, \theta_{1,\text{LO}}), E_2(\pi, \theta_{1,\text{LO}}),\) and \(E_2(3\pi/2, \theta_{1,\text{LO}})\) are aligned at the same value when \(\theta_{1,\text{LO}} = \pm \pi/4\), that is, the phase data of the QPSK signal is erased. The ILLD will, therefore, be successfully injection-locked to the incoming data-erased signal. The regeneration of the carrier power by the circuit shown in Fig. 9 is numerically simulated. The remodulated QPSK signal is calculated by

\[
f(t)(\exp[i k' \Re[f(t) \exp(-i \theta_{1,\text{LO}})]) - i \exp[i k' \Im[f(t) \exp(-i \theta_{1,\text{LO}})])]/2,\tag{7}
\]

where \(f(t)\) is the complex amplitude of the RZ-QPSK signal and \(k'\) multiplied by the peak value of \(|f(t)|\) represents \(k\) in (5). The calculated carrier power (DC component in the spectrum of (7)) for \(k = \pi/\sqrt{2}\) is shown by dots in Fig. 7. The power is normalized so that its peak value at \(\theta_{1,\text{LO}} = \pi/4\) is the same as that

\[\text{Fig. 8.} \quad \text{Numerically calculated spectra. (a) 10-GHz RZ pulse train, (b) 10-Gbaud RZ-QPSK signal, (c) phase-remodulated RZ-QPSK signal in the carrier extraction circuit shown in Fig. 1, and (d) phase-remodulated RZ-QPSK signal in the carrier extraction circuit shown in Fig. 9. Resolution is assumed to be 0.5 GHz.}\]

\[\text{Fig. 9.} \quad \text{Schematic of the QPSK carrier extraction circuit.}\]
evaluated by (4) or (6). The numerical and analytical results agree well near the peak of the carrier power. The discrepancies between them away from the peak is caused by the non-uniform phase modulation in each symbol duration due to the RZ pulse shaping in the numerical simulation. The spectrum of the signal after the phase remodulation modeled by (7) is numerically evaluated and shown in Fig. 8(d), where \( k \) and \( \theta_{LO} \) are \( \pi/\sqrt{2} \) and \( \pi/4 \), respectively. Although some data modulation remains because of the imperfect phase erasure, carrier is regenerated with high suppression of modulation-induced noise.

A preliminary experiment was carried out for 10-Gbaud RZ-QPSK signals using the circuit shown in Fig. 9 [10]. The same LO phase control as in the BPSK carrier extraction is used. Fig. 10 shows optical spectra of (a) the RZ-QPSK signal and (b) the phase re-modulated signal after the dual-electrode MZM. Although the data erasure is not sufficient after the MZM, carrier component is clearly observed. Fig. 11 shows clearly opened eye patterns of I and Q channels at the output of the balanced detectors in the carrier extraction circuit. In this experiment, however, stable long-term carrier extraction and detection of the QPSK signal was not obtained. This is considered to be because the allowable range of deviation of \( \theta_{LO} \) and the contrast of the \( P_{2,QPSK} \) versus \( \theta_{LO} \) curve (ratio of the lowest to the highest values of \( P_{2,QPSK} \)) are smaller. Efforts toward more precise phase tracking in the feedback control will be needed.

![Fig. 10. Optical spectra of (a) 10 Gbaud RZ-QPSK signal and (b) phase-remodulated QPSK signal after the dual-electrode MZM. Wavelength resolution is 0.01 nm.](image)

![Fig. 11. Eye patterns of I (upper) and Q (lower) channels of the 10 Gbaud RZ-QPSK signal.](image)
4 Conclusion

A novel simple scheme of carrier extraction from carrier-less phase-modulated signals is proposed. This scheme requires neither high-speed signal processing in the electrical domain nor high-power nonlinear optical signal processing. Successful carrier extraction from 10 Gb/s RZ-BPSK signal and error-free homodyne detection were demonstrated. The scheme can be extended to carrier extraction from carrier-less QPSK signals.

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