

# Compensation of quadrature imbalance in an optical coherent OQPSK receiver in presence of frequency offset

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**Abstract** In this paper, we describe the impact of quadrature imbalance (QI) in the presence of frequency offset in an optical coherent offset quadrature phase shift keying (OQPSK) receiver. Arbitrary conjugate misalignment was realized in a  $2 \times 4$   $90^\circ$  optical hybrid, and the ellipse correction (EC) method of quadrature imbalance was applied in our simulation. In the case of transmission, the EC method can significantly improve the system performance.

**Keywords** offset quadrature phase shift keying (OQPSK), quadrature imbalance (QI), ellipse fitting, frequency offset

## 1 Introduction

In recent years, there has been renewed interest in the research community in coherent optical communication systems [1–4]. The most promising detection technique for achieving high spectral efficiency is coherent detection with polarization multiplexing, as symbol decisions are made using the in-phase (I) and quadrature (Q) signals in the two fields polarizations, allowing information to be encoded in all available degrees of freedom. Offset quadrature phase shift keying (OQPSK) is one of the modulation formats that has attracted attention lately because of its superior transmission characteristics.

Ideally, the I and Q channels of a quadrature communication system are orthogonal to each other. However, implementation imperfections (e.g., incorrect bias points settings for the I-, Q-, and phase ports, imperfect splitting ratio of couplers, photodiodes sensitivity mismatch, and misadjustment of the polarization controllers) can create

amplitude and phase imbalances that destroy the orthogonality between the two received channels and degrade performance of the OQPSK system. Also, in practice, phase diversity receivers are vulnerable to imperfections in the optical  $90^\circ$  hybrid, which result in direct current (DC) offsets and both amplitude and phase errors in the received signals. These effects give rise to quadrature imbalance (QI) in a communication system [5,6].

In the paper, we first show the simulated optical coherent OQPSK system. Then, the principle of ellipse correction (EC) method is introduced in detail. In the time domain, QI tilts and squeezes the square constellation into a diamond shape. What's more, frequency offset continuously rotates the constellation. In the presence of both QI and frequency offset, the constellation becomes elliptical. Finally, we find that, in the case of transmission, the EC method can significantly improve the system performance.

## 2 System configuration

The impact of nonorthogonality between the I and the Q channels was investigated by simulating the optical OQPSK coherent system shown in Fig. 1. The transmitter was driven with two 50-Gb/s NRZ data streams to provide the OQPSK modulation with two bits encoded in each symbol using the phase of the optical field. The transmit laser and the local oscillator (LO) linewidths were set to 0. An optical  $90^\circ$  hybrid at the receiver side was modeled to mix the transmitted signal and the LO signal before the in-phase and quadrature signals were detected with square-law photodiodes.

## 3 Principle of EC method

Taking advantage of balanced photo-detection, the output signals of the optical hybrid were converted to electrical

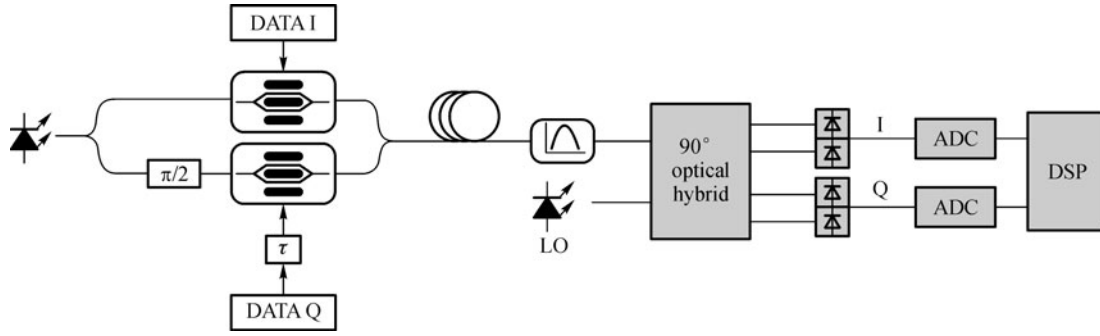


Fig. 1 Simulated optical coherent OQPSK system

signals. If we assume phase-shift-keying modulated incoming signal and ac-coupled photodiode, two received signals can be written as

$$\begin{aligned} I_x &= A \cos \theta, \\ I_y &= B \sin (\theta + \phi), \end{aligned} \quad (1)$$

where  $\theta$  represents all the phase contributions same for the two signals, including bit information, laser linewidth-related phase noise, and frequency and phase offsets originated from LO.  $A$  and  $B$  are constants.  $\phi$  is the conjugate misalignment which is an offset from  $90^\circ$ .  $I_x$  and  $I_y$  are the I and Q signals, respectively. Their relationship can be expressed as [4]

$$\frac{I_x^2}{A^2} - \frac{2I_x I_y \sin \phi}{AB} + \frac{I_y^2}{B^2} - \cos^2 \phi = 0. \quad (2)$$

In other words, the constellation diagram of the digitized received signals forms an ellipse in general. It becomes a perfect circle when  $A = B$  and  $\phi = 0$  that implies normalized signals and  $0^\circ$  conjugate misalignment. In our simulation,  $\phi$  was determined by fitting the constellation of the received signals with Eq. (2).

At first, the two sample sequences were normalized to have the same amplitudes, and then they were combined to be a complex received signal. In order to compensate the conjugate misalignment, the EC method, which is described in Fig. 2, was used in the signal processing. Ellipse fitting finds the least square ellipse that is best fitted to the constellation of the digitized received signal [5,6].

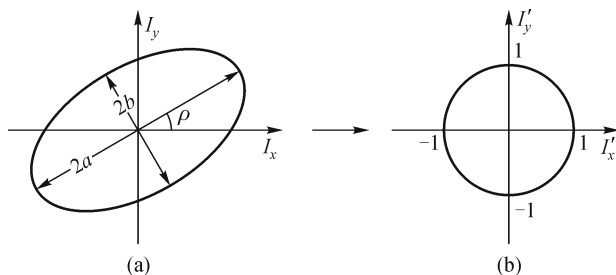


Fig. 2 EC method by transformation of Eq. (3)

We can obtain the ellipse with major axis of  $2a$ , minor axis of  $2b$ , and the rotation angle of  $\rho$  respect to  $I_x$ -axis as described in Fig. 2(a). Simple transformation given by [4]

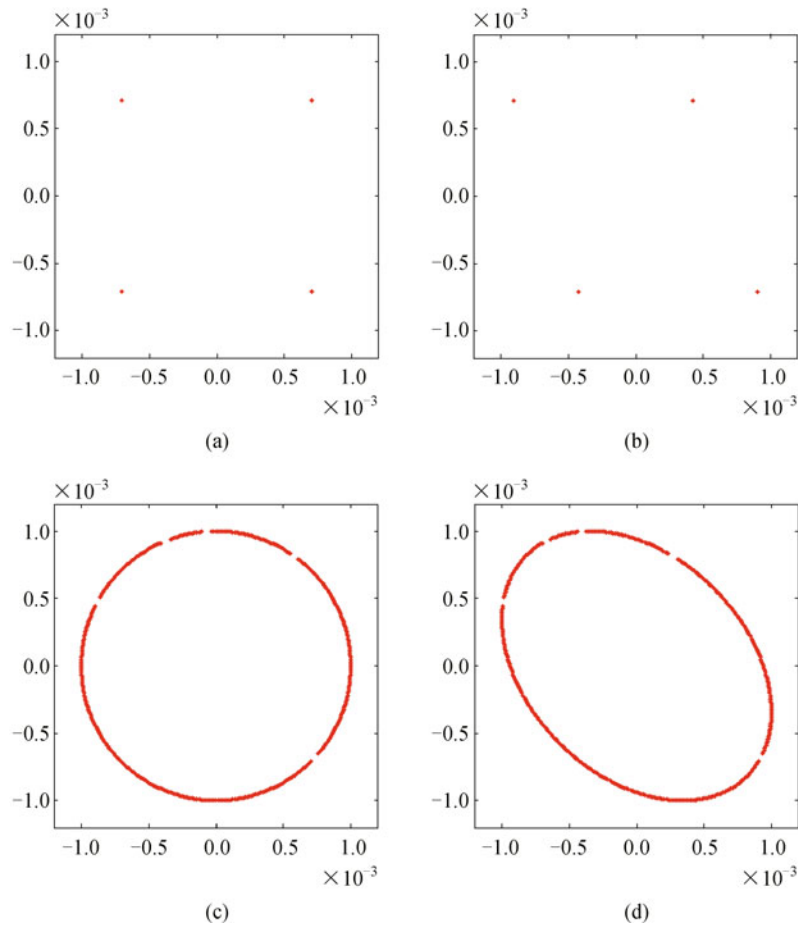
$$\begin{aligned} I'_x &= \frac{I_x \cos \rho + I_y \sin \rho}{a}, \\ I'_y &= \frac{-I_x \sin \rho + I_y \cos \rho}{b}, \end{aligned} \quad (3)$$

reshapes the ellipse shown in Fig. 2(a) into a perfect circle shown in Fig. 2(b).

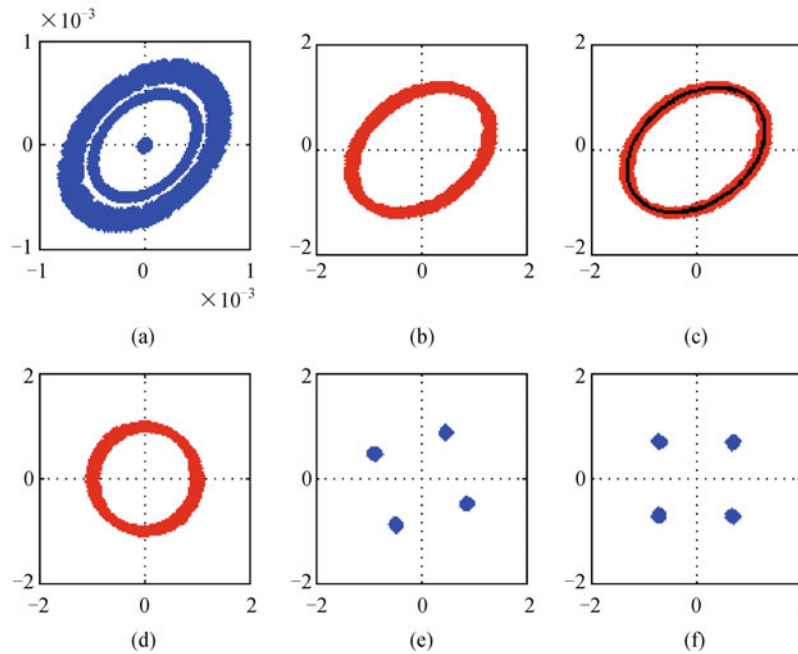
## 4 Analysis and discussion

The impact of QI and frequency offset on received constellation diagrams can be visualized separately, using simulation. In Fig. 3(a), the ideal constellation, when no impairments are present, is shown. In the frequency domain, the presence of QI contaminates the single sideband intermediate frequency (IF) spectrum produced by the phase-diversity receiver with an attenuated image of the unwanted sideband, which leads to a degradation of the system performance [7]. In the time domain, QI tilts and squeezes the square constellation into a diamond shape (Fig. 3(b)) [8]. Further more, frequency offset continuously rotates the constellation (Fig. 3(c)). In the presence of both QI and frequency offset, the constellation becomes elliptical (Fig. 3(d)).

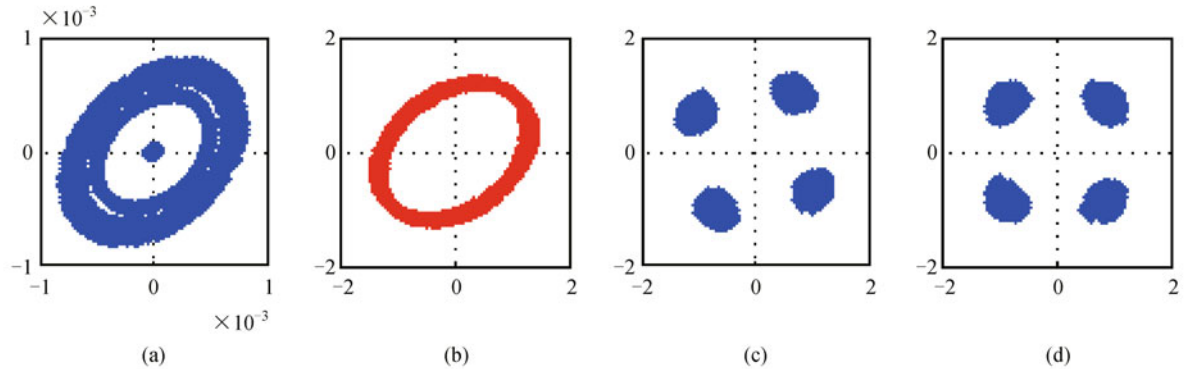
Figure 4 shows an example where the QI correction algorithm has been applied to a received signal with QI. Figure 4(a) shows the constellation diagram when frequency offset between the received optical signal and LO was 200 MHz. Conjugate misalignment was obtained by fitting the constellation with Eq. (2). In the case of Fig. 4(a),  $\phi$  was set to  $20^\circ$ , which was adjustable. Fiber transmission inevitably introduces chromatic dispersion (CD), which was compensated with a time domain method in our simulation (Fig. 4(b)) [9]. The black solid line shown in Fig. 4(c) is the fitted ellipse curve, and the EC method of Eq. (3) transformed the constellation to that shown in Fig. 4(d). The frequency offset between the



**Fig. 3** (a) Ideal constellation; (b) impact of QI; (c) impact of frequency offset; (d) impact of QI in presence of frequency offset



**Fig. 4** (a) Received constellation; (b) after CD compensation; (c) fit constellation into ellipse; (d) transform ellipse into circle; (e) after frequency error correction; (f) after phase error correction



**Fig. 5** (a) Received constellation; (b) after CD compensation; (c) after frequency error correction; (d) after phase error correction

received optical signal and LO was estimated by the phase increment estimation algorithm (Fig. 4(e)) [10]. What remains after the frequency offset between the laser of the transmitter and the LO laser of the receiver has been compensated for is the phase difference between the lasers. We adopted a method, introduced in Ref. [11] in detail, to estimate and correct carrier phase in our simulation (Fig. 4(f)).

Figure 5 shows the corresponding example without applying the QI correction algorithm. The same system configuration, CD compensation algorithm, frequency offset compensation algorithm and carrier phase estimation algorithm were adopted in the corresponding example. Compared to Fig. 5, the finally obtained constellation points in Fig. 4 are apparently smaller. Therefore, we can easily conclude that the EC method can significantly improve system performance.

## 5 Conclusion

EC method firstly finds the least square ellipse that best fitted to the constellation of the digitized received signal, and then reshapes the ellipse into a perfect circle by means of a simple transformation. Subsequently, the frequency offset between the received optical and LO signals, which is 200 MHz in our simulation, has been estimated and corrected by the phase increment estimation algorithm. In the case of transmission, the EC method can significantly improve the system performance.

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