Polarization-Independent Receivers for Low-Cost Coherent OOK Systems

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***Abstract*—We demonstrate analytically a novel scheme to obtain polarization-independent operation in low-cost coherent OOK receivers, suitable for access networks. We move from a well-known phase-diversity receiver, exploiting a 3 x 3 coupler, three photodiodes, and basic analogue processing. If that receiver is modified to inject the local oscillator (or the signal) into two inputs with proper polarization states, we show, by both mathematical derivation and numerical simulations, that the resulting electrical signal can be polarization-independent; this is attained only if the frequency-detuning between the signal carrier and the local oscillator is high enough, so that intrinsic second order distortions can be spectrally isolated and suppressed by the low-pass filtering of the receiver.**

***Index Terms*—Fiber optic communication, bit error ratio (BER), coherent systems, polarization.**

I. Introduction

AFTER the recent development of coherent systems for core networks, it is expected that coherent technology can be effectively exploited also in access networks, namely wavelength division multiplexing passive optical networks (WDM-PON) [1]–[5]. However, up to now most of the proposed approaches rely onto similar system solutions as for core networks, i.e. expensive optical and/or electronic devices (including advanced digital signal processing).

Recently, the EU-funded COCONUT project started tackling this key issue, aiming at providing ultra-dense WDM-PON by exploiting coherent detection, realized by common components (e.g. DFB lasers) and simple processing (e.g. basic analog processing) [6]. Among the first COCONUT results, it was demonstrated that a 3×3 phase diversity receiver, realized with DFBs and analog processing [7], can provide ultra-dense WDM-PON operation with intensity-modulated signals at 1.25 Gbit/s [8]. Furthermore, the receiver had -48 dBm sensitivity and required no special control of the local oscillator (LO), whose optical frequency could be allowed to move quite far from the signal carrier frequency. A similar receiver was demonstrated in [9], using DSP and polarization diversity, to detect polarization-multiplexed signals with complex modution formats.

However, the above proposed analog receiver suffered from the inherent issue of coherent detection, i.e. it was polarization sensitive [8]. The issue of polarization-dependency, which is intrinsic in the coherent detection process, has been tackled in the past using various means, including automatic polarization control [10], polarization-diversity (currently implemented in commercial systems) [11]–[13] and polarization scrambling [14], [15]. It can be seen that applying any of the above techniques to a receiver for access network would eventually result into a significant additional complexity, with much higher component cost.

Here we present for the first time to the best of our knowledge novel schemes that allow realizing a polarization-independent coherent receiver: to this aim, we extend the architecture used in [8], with very limited additional complexity. We consider the phase-diversity receiver, with a symmetric 3×3 coupler (1:1:1), and then assume to split and inject the local oscillator (or the signal) in two arms of the coupler, with orthogonal States of Polarization (SoP). We leave all other parts of the receiver untouched, including the processing.

We first investigate the receiver performance by means of mathematical derivation. Although we derive that in the pure-homodyne regime the electrical signal at the receiver output is highly affected by polarization variations, so that the receiver cannot operate properly, we also derive conditions under which a clean electrical signal is attained, which is independent on the SoP of the signal. These results are then confirmed by numerical simulations, showing clearly that, under proper design and operation of the receiver, polarization independence (PI) is clearly attained.

II. Operating Principle

We report in Fig. 1 the main scheme (a) and a possible equivalent alternative (b) for the proposed receiver. As can be seen, in the first case the signal enters one of the inputs of the 3×3 coupler, whilst the LO enters at 45° a polarization beam splitter (PBS), it is split into two orthogonal components (which have thus the same amplitude) and these last enter then the 3×3 coupler. The connections between the PBS and the coupler are assumed not to vary in time the SoP of the lightwaves, which can be simply attained.

As an alternative, the input signal is first split by a polarization beam Splitter (PBS), and then the two orthogonal SoP components enter the first two arms of the coupler, after rotating the 2^{nd} component by 90 degrees; the LO enters the 3^{rd} arm and all the three fields have the same SoP. All other parts of the receiver are untouched, including the processing. As a real PBS usually has some non-negligible insertion loss

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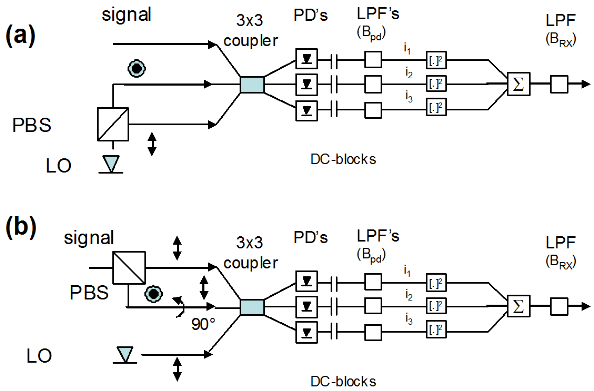

Fig. 1. Scheme of the proposed receiver with the option to have the PBS either on the LO (a) or on the signal (b).

and there is no significant constraint on the power of the LO [8], a better sensitivity should be obtained by using the first configuration. Since we will see later that the two options have very similar performance, we will thus first restrict the mathematical analysis to the first case.

After the coupler, the signals are detected by the three photodiodes (PDs); their output currents pass through identical DC-blocks and low-pass filters (LPF), which have bandwidth B_{pd}. Finally the currents are squared and summed (Σ), to obtain the final signal, which is further low-pass filtered, by a LPF having bandwidth B_{RX}, before being injected into a common clock and data recovery circuit (CDR). In a real implementation, the $\Sigma-$block and the final low-pass filter could be most likely implemented in a single device with proper bandwidth, although the combination of an adder of very wide bandwidth and an optimized low pass filter is also feasible.

III. Mathematical Analysis

In order to investigate the behavior of the proposed circuit, we first model it analytically. We assume that the signal and the LO have a frequency detuning of $\Delta\nu$ and that the signal can have a random polarization, thus its Jones vector can be written as

$$U(t) = \begin{pmatrix} r(t)\, e^{i(2\pi\ \Delta\nu\ t)} \cos(\varphi) \\ r(t)\, e^{i(2\pi\ \Delta\nu\ t+\psi)} \sin(\varphi) \end{pmatrix} \tag{1}$$

where $r(t)$ is the modulated amplitude, φ is the orientation of the main axis of the polarization ellipse and ψ is the SoP ellipticity angle ($\psi = 0$ for linear polarization). Without loss of generality and for the sake of clarity, let us assume that the two components of the LO entering the coupler have same amplitude and phase (E_{LO}).

As known, the coupler mixes the three inputs so that, for each polarization j ($j = x$ or y) the three outputs are given by

$$\begin{pmatrix} E_{1,j} \\ E_{2,j} \\ E_{3,j} \end{pmatrix} = \begin{pmatrix} a & b & b \\ b & a & b \\ b & b & a \end{pmatrix} \begin{pmatrix} U_j \\ E^{(2)}_{LO,\,j} \\ E^{(3)}_{LO,\,j} \end{pmatrix} \tag{2}$$

where the LO components are so that $E^{(2)}_{LO,x} = E^{(3)}_{LO,y} = E_{LO}$, (the other two LO components are zeros). The coefficients a and b are simply given by well known expressions for the 3×3 coupler [16]. The three fields at the output of the coupler are then simply written, as an example at the first output we get:

$$E_1(t) = \begin{pmatrix} a\, r(t)\, e^{i(2\pi\ \Delta\nu\ t)} \cos(\varphi) \ + \ b\, E_{LO} \\ a\, r(t)\, e^{i(2\pi\ \Delta\nu\ t+\psi)} \sin(\varphi) + b\, E_{LO} \end{pmatrix}. \tag{3}$$

Assuming, for simplicity, that the photodiodes have very wide bandwidth ($B_{pd} \gg B$), the three currents can be simply derived $i_k = R(|E_x|^2 + |E_y|^2)$, where R is the photodiode responsivity. Using the previous expressions and assuming the DC-block to cancel exactly the CW component due to the LO, we can derive the three currents; as an example we get

$$i_1 = \frac{2}{3} R E_{LO} r(t) \left[\cos\left(2\pi\,\Delta\nu t - \psi + \frac{2\pi}{3}\right)\sin(\varphi) + \cos\left(2\pi\,\Delta\nu t + \frac{2\pi}{3}\right)\cos(\varphi)\right], \tag{4}$$

where we neglect the much smaller direct-detection term. By squaring and summing the currents, we derive the signal $S(t) = i_1^2 + i_2^2 + i_3^2$. We note that in the receiver implementation, $S(t)$ can be equivalently obtained by $S(t) = (i_1 - i_2)^2 + (i_3 - i_1)^2 + (i_3 - i_2)^2$, with no significant change in the final performance (the two expressions are equivalent if the coupler is ideal).

When making $S(t)$ explicit, we get a complex expression, which, however, after some simplifications, gives:

$$S(t) = \frac{2}{3} R^2\ E^2_{LO} r(t)^2 \left(1 - \sin(2\varphi) \times \sin\left(\frac{\pi}{6} - 4\pi\ \Delta\nu\ t - \psi\right)\right). \tag{5}$$

As we see, $S(t)$ includes the information on the signal intensity modulation $r(t)$, which is multiplied by the terms in the parenthesis. However, within the parenthesis, we have a constant unitary term and another spurious term. The last is responsible for polarization-dependence of the signal as it depends on both φ and ψ. Moreover, from Eq. 5 we see that if $\varphi = n\pi/2$, ($n = 0, 1, \ldots$) the overall second term in the parenthesis vanishes, which corresponds to the signal being aligned to either X- or Y-polarization (similar as in [7] and [8]). In those two special cases, clearly, the signal only beats with one of the two parts of the LO. However, in any other case, the signal entering with a random SoP will produce also the 2nd contribution in the parenthesis. This spurious term can completely close the eye diagram (if $\varphi = n\pi/2 + \pi/4$).

We also note that Eqn. 5 expresses an electrical signal made of two contributions: the first is the correct signal, always centered at baseband, and the second is a copy of the very same signal translated at $2\Delta\nu$. This spurious term has a amplitude depending on the signal SoP: as said, it may be zero in some particular cases, but in a generic case it is non-zero and non-negligible.

If we have perfect homodyne ($\Delta\nu = 0$), this spurious term has complete spectral overlap with the signal, which is then unacceptably distorted. On the other hand, if we set a non-negligible $\Delta\nu$ (intradyne regime) we see that the spurious term is oscillating at $2\varDelta\nu$. We can exploit that feature in order to achieve polarization-independence: since $S(t)$ is usually low-pass filtered, a suitable choice of the frequency detuning and of the value of B_{RX} can allow reducing substantially the polarization dependence. Of course B_{RX} cannot be reduced as you like, since it must not induce inter-symbol interference on the signal, and cannot be too wide to limit the amount of noise. Usually the equivalent filtering function of the receiver is a Bessel filter whose bandwidth B_{RX} is 75% the signal bit rate B. Giving this value for granted, a careful choice of $\varDelta\nu$ can allow achieving polarization-independence: we see indeed that we reach PI-detection if we set $\varDelta\nu$ so that the spurious term has very limited spectral overlap with the signal. This means that, although exact homodyne detection is not acceptable, intradyne detection with significant frequency detuning can be a suitable choice. Clearly, the detuning must be significant in order to achieve PI. Furthermore it would be also required that the photodiodes have slightly wider bandwidth than the minimum for homodyne detection. In the particular case of 1.25 Gbit/s signals, this has very limited practical impact.

IV. Numerical Simulations

In order to test this concept, we simulate the performance of a proposed coherent receiver by means of numerical simulations. In order to have a reference to [8], we model a OOK signal sequence at 1.25 Gbit/s, produced by CW lightwave modulated by an external amplitude modulator (1.8 GHz bandwidth). This choice of bit rate gives no loss of generality: as can be understood from the previous section, all these results could be attained at any chosen bit rate (B), provided that $\varDelta\nu$ and the filter bandwidth values are re-scaled accordingly.

In order to test PI, the signal SoP is scrambled by sine-wave modulating φ and ψ at around 6 and 7 MHz, respectively; the signal is then finally injected into the receiver, as previously described, with the two schemes reported above. The LO is assumed to have a linewidth around 2 MHz. We neglect relative intensity noise, for the sake of simplicity. The three output signals from the coupler are photo-detected by three photodiodes ($B_{pd} = 2$ GHz). The CW component of each signal is then removed by a DC-block and the corresponding currents i_k are derived.

The final received signal is then obtained by Eqn. 4. The signal $S(t)$ is then filtered by means of a usual 4$^{\text{th}}$ order Bessel filter ($B_{RX} = 0.93$ GHz); automatic clock recovery and sampling at the centre of the eye diagram then allow estimating the statistics of the signal and extracting the Q factor. Although the Q factor may not be completely accurate, still it provides a good indication of the system performance. As expected, for perfect homodyne ($\Delta\nu = 0$), the eye diagram is completely closed, as a combined result of the polarization scrambling of the signal and the structure of the receiver. In this case the eye diagram shows no improvement from the one obtained for a conventional receiver with a fixed LO SoP and random signal SoP.

However, when increasing the detuning, the clear role of $\Delta\nu$ in our receiver scheme is confirmed. In order to illustrate it,

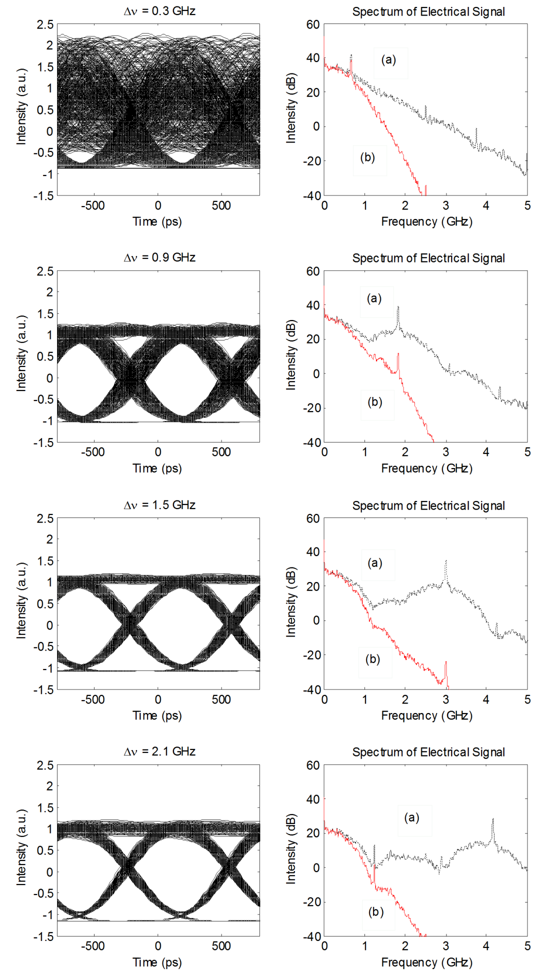

Fig. 2. Received signals for different detuning conditions ($\Delta\nu$). Left: eye diagrams at the output of the first PI-receiver. Right: corresponding electrical spectra before (a) and after (b) the final Bessel filter. In all cases, a SoP-scrambled signal at 1.25 Gbit/s is assumed.

we report in the left column in Fig. 2 the eye diagrams obtained, for our polarization-scrambled signals, at the output of the first type of PI-receiver for different detuning conditions ($\varDelta\nu$). When increasing this parameter we move from a condition of closed eye diagram ($\varDelta\nu = 0.3$ GHz) up to a clearly open eye ($\varDelta\nu = 0.9$ or 1.5 GHz).

We report also in the right column in Fig. 2 the corresponding electrical spectra of the signal. Here, for the sake of clarity, we present two types of curves: the first refers to an ideal signal as it would be obtained from Eq. 4 (a) (it is therefore the result only of the filtering effect of the photodiodes). The second class of curves (b) shows the electrical spectra obtained at the real output of the receiver, i.e. they include also the final low-pass filtering effect. When considering the first signal, we see that, at increasing $\varDelta\nu$, the obtained electrical spectra are quite different: it is confirmed that a crosstalk-like signal arises, centered at $2\cdot\varDelta\nu$, which may be not very clear in the first line ($\varDelta\nu = 0.3$ GHz, where the spectral overlap with the signal is much higher), but becomes apparent when $\varDelta\nu$ is increased. The effect of the Bessel filter is apparent comparing these curves to the curves (b): as the 2$^{\text{nd}}$ order distortions fall outside B_{RX}, they become hardly noticeable

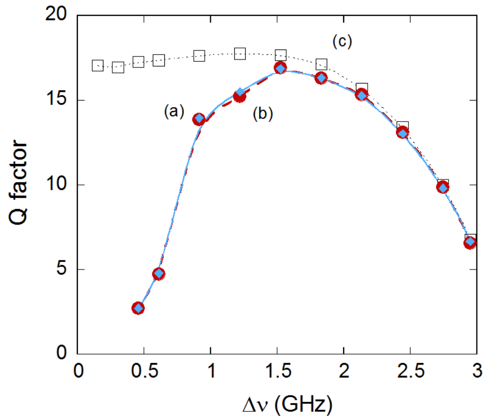

Fig. 3. Estimated Q factor as a function of the frequency separation $\Delta\nu$, for the two receiver schemes shown in Fig. 1, reported as curve (a) and (b), respectively, using a 1.25 Gbit/s signal with varying SoP. For comparison curve (c) reports the same estimation performed using a signal with fixed-SoP and the conventional receiver (with SoP of the LO aligned to the signal SoP).

and are strongly suppressed. All above results are very similar to what is obtained in the second configuration of the proposed PI-receiver, which are thus not included.

Finally, in order to estimate the system tolerance to $\Delta\nu$ values, we estimated the Q factor at different detuning values. These results are reported in Fig. 3, where we present the Q factor for the two phase-diversity receivers shown in Fig. 1, using in both cases a polarization-scrambled signal. Here curve (a) refers to the first configuration (PBS on the LO) and curve (b) refers to the second case (PBS on the signal). As we see, the two curves are practically superimposed and as $2\cdot\Delta\nu$ exceeds the B_{RX} value, the Q factor grows. A high-quality signal is then obtained in a frequency region of almost 1 GHz, which is compatible with usual frequency fluctuations of the DFB lasers controlled by commercial equipment (around $\pm$50 MHz [8]). It is to be clearly noted that if $\Delta\nu$ is further increased, the Q factor decreases; this is however common to the case of the usual receiver (i.e. non-PI). In order to confirm this last assumption, in Fig. 3 we also report the curve of the estimated Q-factor value for this type of receiver (curve c), but for a signal having a fixed SoP (aligned to the LO SoP). As can be seen, at high values of the detuning, the three receivers have practically the same performance.

V. Conclusion

We have presented, for the first time to the best of our knowledge, a novel scheme to achieve polarization-insensitive operation of a low-cost coherent receiver. The scheme uses a common 3×3 fiber coupler and achieves polarization-insensitive operation by inserting an additional lightwave at the unused input of the coupler. When the detuning between signal and LO is low, this receiver hugely suffers from variations of the SoP of the signal, similar to the usual receivers. However if the detuning is higher, the signal at the receiver output is not affected by the SoP variations. Proper choice of the $\Delta\nu$ value allows optimization of the receiver, with quite broad system tolerance, i.e. no need of precise frequency locking.

Compared to the polarization-sensitive version [7], [8], polarization-independence is here achieved by only adding a PBS; this represents a very modest increase of complexity and it is thus expected that the PI-receiver might be quite simpler and cost-effective than the corresponding alternatives based on the other techniques used to attain PI.

The proposed scheme has been presently demonstrated assuming analog processing and OOK signals, a format that has a number of positive features for the considered applications in access networks [8]. Using analog processing the extension to other modulation formats (e.g. DPSK) might be hard, and it is still being investigated.

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