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LETTER TO THE EDITOR

Phase detection in optical communication systems through phase conjugation

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Abstract. A novel phase-detection scheme based on phase conjugation is proposed. Its use has all the advantages offered by the conventional heterodyne detection technique but simplifies the receiver design considerably since neither a balanced receiver nor a polarization-diversity receiver are required.

The use of homodyne or heterodyne detection has not become practical for optical communication systems in spite of the advantages offered by such coherent lightwave systems [1, 2]. The major reason behind it is related to the complexity of coherent optical receivers, resulting from the need to counteract the effects of intensity, phase and polarization fluctuations [1]. In this letter I propose an alternative technique for phase detection that is similar to coherent detection from the standpoint of functionality, but allows us to overcome some of its practical limitations. The basic idea is to use four-wave mixing [3] (FWM) to generate a spectrally inverted, phase-conjugated wave, interfere it with the received signal, and detect the resulting interference pattern. The use of phase conjugation for dispersion compensation through midspan spectral inversion has attracted considerable attention recently [4–6]. The proposed scheme can be implemented in a similar way, with the main difference being that the phase conjugation is performed at the receiver end.

Figure 1 shows a schematic of an optical receiver making use of phase conjugation for phase detection. The received signal at the carrier frequency ω_0 is phase-conjugated in an optical fibre [4–6] by using a pump laser operating at the frequency ω_p. The pump–signal detuning, $\Omega = \omega_p - \omega_0$, and the minimum-dispersion wavelength of the fibre are chosen such that the FWM process is nearly phase matched [3]. The conjugated wave generated at the frequency $\omega_c = 2\omega_p - \omega_0$ accompanies the pump and signal waves, resulting in a total electric field $E(t)$ at the photodetector of the form

$$E(t) = \tfrac{1}{2}\{E_p \exp(-\mathrm{i}\omega_p t) + E_s \exp(-\mathrm{i}\omega_0 t) + \eta E_p^2 E_s^* \exp[-\mathrm{i}(2\omega_p - \omega_0)t]\} + \mathrm{CC} \qquad (1)$$

where E_p and E_s are the pump and signal fields, η is related to the efficiency of phase conjugation and CC stands for the complex conjugate. Since the phase of η can be absorbed in the pump phase, η is assumed to be real. The photocurrent $I = R|E|^2$, where R is the detector responsivity, consists of both DC and AC terms, the latter resulting from interference among pump, signal and conjugate waves. It can be written as

$$\begin{aligned} I(t) = R[P_p + (1 + \eta^2 P_p^2)P_s] + 2R\sqrt{P_s P_p}(1 + \eta P_p)\cos(\Omega t + \phi_s - \phi_p) \\ +2R\eta P_p P_s \cos(2\Omega t + 2\phi_s - 2\phi_p) \end{aligned} \qquad (2)$$

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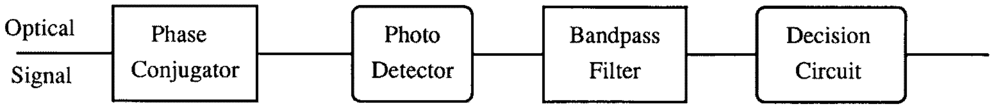

Figure 1. Schematic of an optical receiver making use of phase conjugation for phase detection.

where $P_p = |E_p|^2$ and $P_s = |E_s|^2$ are pump and signal powers, respectively. Note that for $\eta = 0$ (no phase-conjugate wave), equation (2) reduces to conventional heterodyne detection.

The DC term of the photocurrent, $I_{DC} \approx RP_p$, is dominated by the pump power. The AC term oscillating at the frequency Ω is similar to heterodyne detection. The new term oscillating at 2Ω is due to phase conjugation. The proposed technique differs from conventional heterodyne detection in as much as it uses the 2Ω terms for recovering the transmitted signal. A bandpass filter centred at 2Ω can be used to recover the baseband signal; a decision circuit then reconstructs the bit stream coded through amplitude-, phase-, or frequency-shift keying (see figure 1).

Since a pump laser acting as a 'local oscillator' is still needed, one may ask with justification whether anything is gained by using phase conjugation. The answer is that the proposed phase-conjugation technique allows operation near the shot-noise limit, in a way similar to the case of heterodyne detection, while simplifying the receiver design considerably. In fact, it virtually eliminates the problems associated with the intensity noise of the local oscillator and with the polarization fluctuations of the received signal, thereby requiring neither a balanced receiver nor a polarization-diversity receiver.

To understand why a balanced receiver is not required, consider the signal-to-noise ratio (SNR) of the proposed detection scheme given by [1]

$$\mathrm{SNR} = \frac{I_{AC}^2(2\Omega)}{\sigma_s^2 + \sigma_T^2 + \sigma_I^2} = \frac{2R^2\eta^2 P_p^2 P_s^2}{2qRP_p\Delta f + \sigma_T^2 + 2R^2P_p^2(\mathrm{RIN})\Delta f} \tag{3}$$

where σ_s^2, σ_T^2 and σ_I^2 are the current variances due to shot, thermal and intensity noise, respectively, and RIN is the relative intensity noise of the pump laser assumed to be constant over the receiver bandwidth Δf. In contrast, the SNR for the case of heterodyne ($\eta = 0$) is given by [1]

$$\mathrm{SNR} = \frac{I_{AC}^2(\Omega)}{\sigma_s^2 + \sigma_T^2 + \sigma_I^2} = \frac{2R^2 P_p P_s}{2qRP_p\Delta f + \sigma_T^2 + 2R^2P_p^2(\mathrm{RIN})\Delta f}\,. \tag{4}$$

A comparison of (3) and (4) shows that while the total noise power is the same in both cases, the electrical signal power varies with P_p and P_s quadratically rather than linearly. This quadratic dependence has several important consequences. First, an optical amplifier (such as an erbium-doped fibre amplifier) can be used, if necessary, to amplify both P_p and P_s to counteract the low efficiency of the FWM process. Second, it is relatively easy to realize $\sigma_s^2 \gg \sigma_T^2$ (by increasing the pump power) and operate in the shot-noise limit. Third, in contrast with (4), for which the SNR attains a maximum for an optimum pump power and begins to degrade beyond it, the SNR of the phase-conjugation-based detection scheme keeps on improving with increasing pump power, attaining a value $\mathrm{SNR} = (\eta P_s)^2/[(\mathrm{RIN})\Delta f]$ in the limit of infinite pump power.

It is important to note that the phase noise of the pump laser affects the receiver performance in much the same way as it affects the performance of heterodyne receivers since the pump phase appears explicitly in the last term of (2). However, signal phase can be recovered as long as the pump phase changes relatively little over the duration of a single bit. This condition can be easily met by using pump lasers whose linewidth is smaller than the bit rate. Distributed feedback semiconductor lasers with linewidths below 100 MHz should satisfy this requirement for most lightwave systems.

Polarization fluctuations occurring in conventional (non-polarization-preserving) fibres are known to impose a severe limitation for coherent detection to the extent that the use of a polarization-diversity receiver is a necessity [1]. The proposed scheme does not require matching of the pump and signal polarizations, thereby eliminating the need of polarization-diversity receivers. The only requirement is that the signal and phase-conjugate waves have the same polarization. This can easily be accomplished optically by using the techniques developed for implementing dispersion-compensation schemes in which the FWM efficiency is independent of the signal polarization [7, 8].

In conclusion, a novel phase-detection scheme based on phase conjugation is proposed. Its use has all the advantages offered by the conventional heterodyne detection technique but simplifies the receiver design considerably since neither a balanced receiver nor a polarization-diversity receiver are required.

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