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Homodyne Coherent Detection of ASK and PSK Signals Performed by a Sub-Carrier Optical Phase-Locked Loop

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***Abstract*—Optical transmission systems based on homodyne coherent detection of 2-ASK and pilot carrier 2-PSK signals have been implemented. ASK data has been transmitted at 2.5 Gbps, while 2.5 Gbps and 10 Gbps PSK systems have been tested. The proposed architecture is based on a new optical phase locked loop founded on sub-carrier modulation and leads to new compact integrated receivers and new transmission formats, thus opening new opportunities for future optical systems.**

***Index Terms*— Optical phase locked-loops, coherent detection, amplitude shift keying (ASK), phase shift keying (PSK).**

I. Introduction

In most telecommunication fields outside the optical scenario, transmission systems are based on coherent detection, i.e., on a receiver where a Phase-Locked Loop (PLL) tracks the frequency and phase of the received signal. The local oscillator signal is then mixed to the received signal in order to obtain either homodyne or heterodyne detection. Coherent systems have several advantages, mainly related to:

- Increase of the receiver sensitivity
- Compatibility with complex modulation formats, such as M-PSK, M-QAM, etc.

Coherent systems were investigated in the field of optical transmission in the years around 1990 [1-8], mainly for sensitivity issues, but they never found commercial application due to their complexity and cost, and secondly, because RX sensitivity issues were overcome by the introduction of EDFA's. Even though sensitivity is no longer a major issue, coherent optical detection may have a fundamental role in future optical transmission systems. In fact:

- Coherent (homodyne) detection would open the way to those modulation formats that are largely and successfully used in other telecommunication fields, such as M-PSK, M-QAM and others. All these formats allow a much higher spectral efficiency than conventional Intensity Modulation (IM), by a factor log2(M). For example, 8-PSK bandwidth is 3 times narrower than standard IM-DD, given the same bit rate. This also allows the use of narrower band electronic and optoelectronic components in the TX and RX, by the same factor.
- Besides amplitude, coherent detection allows also phase information recovery at the RX, a feature that opens completely new applications in receiver equalization for dispersion and PMD compensation. Consequently, all techniques used in equalization of RF receivers, such as multipath fading equalization, could in principle be applied to optics [10].
- Coherent detection allows separating closely spaced DWDM channels without requiring narrow optical filters, since channel selection is obtained directly at the baseband by electrical filtering [3].

Nowadays, we believe that there is again a rationale for optical coherent systems, as it has been recently addressed in several works [10-11]. This paper proposes PSK and ASK coherent optical communication systems, which are derived from common architectures, described in previous works [1,3,6], by substituting the optical phase-locked loop (OPLL) with a novel one based on subcarrier modulation [12]. Performance of 2.5 Gbps ASK and PSK coherent systems is tested as well as a 10 Gbps PSK transmission system.

II. Experimental Setup

Fig. 1 shows the experimental setup for the PSK transmission system we developed. Based on this scheme two experiments at data rates of 2.5 Gbps and 10 Gbps were carried out. The PSK coherent receiver is based on the SC-OPLL [12] and contains an optical 3 dB coupler, an amplified photodiode (Ph1), a loop filter and an Optical Voltage Controlled Oscillator (OVCO). Ph1 has a bandwidth of 1.8 GHz, a responsivity of 800 V/W and sensitivity of -24 dBm (BER=10^{-9}). For detecting the received data, we used two different photodiodes: one has 1.8 GHz bandwidth and sensitivity of -24 dBm (BER=10^{-9}) for a transmission rate of 2.5 Gbps and the other has 8 GHz bandwidth and sensitivity of -18 dBm (BER=10^{-9}) for a rate of 10 Gbps. The loop filter is a first order active filter characterized by the time constants τ_1 = 1.5 μs and τ_2 = 0.39 μs. Due to the propagation delay introduced by electrical and optical components in the loop

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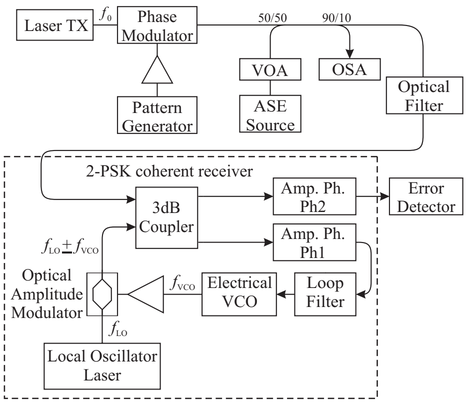

Fig. 1. Experimental setup of 2.5 and 10 Gbps PSK transmission systems.

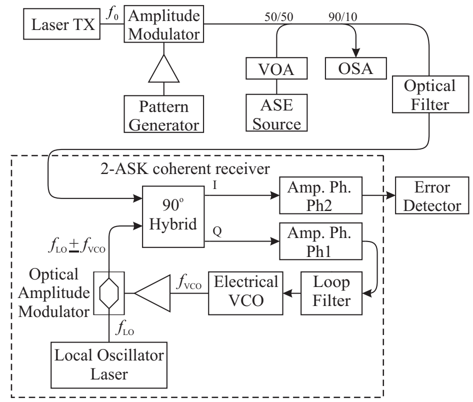

Fig. 2. Experimental setup of 2.5 Gbps ASK transmission system.

the overall delay is approximately 10 ns. The OVCO is the key element and includes a 20 GHz electrical VCO with 500 MHz/V tuning coefficient, a 40 GHz power driver, a 40 GHz $LiNbO_3$ amplitude modulator. Biasing the external Mach-Zehnder amplitude modulator at a null of its transfer function, as described in [12], the OVCO produces two main subcarriers at frequencies $f_{LO} \pm f_{VCO}$ with a spurious residual carrier at frequency f_{LO}. The LO wavelength has been set such that the main sub-carrier $f_{LO} + f_{VCO}$ is able to lock the received signal at frequency f_0. The power at the output of OVCO is 0 dBm. The local oscillator (LO) laser is an external cavity tunable laser, whose typical linewidth is lower than 700 kHz. By using the theory developed in [3] and its generalization for finite loop delay time, we performed a numerical integration in order to analyze the relationship between the linewidth of our lasers (LO and signal) and the optimum PLL bandwidth (an approximate theory on loop delay time effect is shown in [8]). In our case a PLL bandwidth of almost 3 MHz has been used in order to minimize the effect of the laser phase noise and loop delay time, as experimentally demonstrated in [12]. Therefore, the PLL introduces a high-pass filtering that affect the received phase signal (leaving the amplitude unaltered) and deteriorate the performance of PSK modulation format (while does not affect ASK). In order to avoid the effect of such a filtering, we had to transmit pseudo random bit sequences (PRBS) no longer than 2^7-1. This working condition is not typical in optical transmission systems but does not limit the proof of concept of our PSK transmission systems. The problem of pattern dependency can be solved using better linewidth lasers, which require a lower PLL bandwidth, or upgrading the proposed architecture to a more complex decision driven PLL [9].

The SC-OPLL belongs to the family of the pilot carrier coherent optical receivers [2] and requires that the transmitted signal contains the PSK data and a residual carrier. Thus, the transmitter includes an external cavity tunable laser with the same characteristics of the LO laser, a $LiNbO_3$ 10 Gbit/s phase modulator that requires 11 V for producing a 180° phase shift. For the transmission of the 2-PSK signal, the modulation angle was adjusted to ±57°, by leaving a residual carrier containing 30 percent of the transmitted power. The Amplified Spontaneous Emission (ASE) noise and the Variable Optical Attenuator (VOA) add a variable amount of noise to the transmitted signal, having constant power; this configuration allows changing the Optical Signal to Noise Ratio (OSNR), measured by an Optical Spectrum Analyzer (OSA) with a resolution bandwidth of 0.1 nm, and keeping constant the received signal power to -15 dBm at the receiver (both 2.5 and 10 Gbit/s experiments). The optical filter limits the noise power and has an optical bandwidth of 0.7 nm.

Fig. 2 shows the schematic of the 2.5 Gbps 2-ASK transmission system. The receiver is the simple SC-OPLL in which the 3 dB combiner is replaced by a 90° hybrid which combines the two input signals in phase, at the "I" output port, and in quadrature, at the "Q" output port. Fig. 3 shows the time evolution of the "I" and "Q" 90° hybrid outputs after photodetection. The substitution is necessary because, as every PLLs do, the SC-OPLL locks in quadrature to the received signal. The same principle was used in [1]. The 90° hybrid is a cube divided into 4 parts by two planar surfaces, which work, respectively, as a polarizing and a polarization independent beam splitters. A similar configuration was employed in [7]. The loop filter, in this case, has time constants τ_1 = 82 ns and τ_2 = 64 ns. The OVCO includes a 6 GHz electrical VCO with 100 MHz/V tuning coefficient, a 10 GHz power driver, a 10 GHz LiNbO3 amplitude modulator and an external cavity tunable laser. The transmitter is a typical intensity modulation (IM) transmitter and includes an external cavity tunable laser, a $LiNbO_3$ intensity modulator driven by a 2.5 Gbps NRZ signal. In this case, the intensity-modulated signal is not affected by the PLL high-pass filtering, which only influences the phase signal and the transmitted sequence is 2^{31}-1 long PRBS. The signal power is

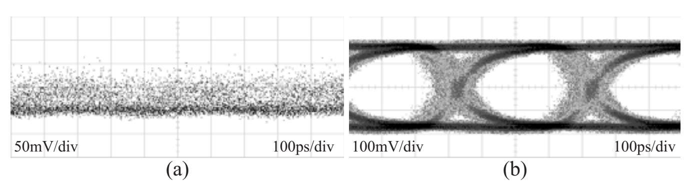

Fig. 3. Quadrature (a) and in-phase (b) optical 90° hybrid output after photodetection. The signal in (b) is also affected by a limiting amplifier.

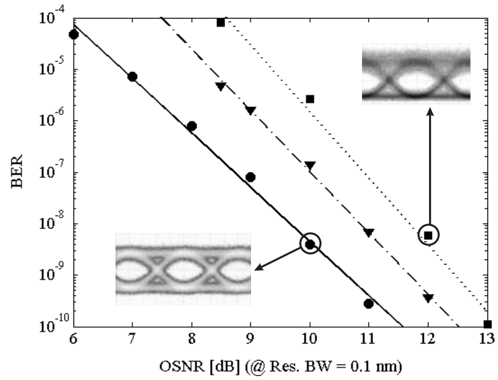

Fig. 4. Measured BER versus OSNR of 2.5 Gbps data for ASK (triangles), PSK (circles) and IMDD (squares) transmission systems.

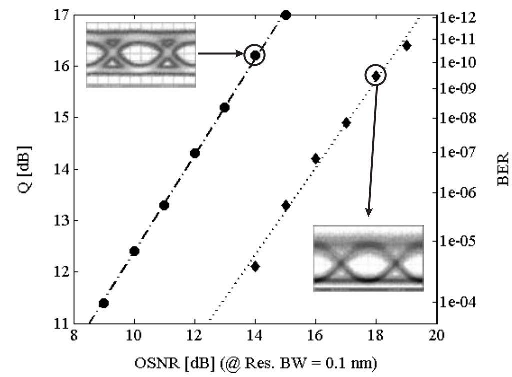

Fig. 5. Measured Q-BER versus OSNR of 10 Gbps data for PSK (circles) and IMDD (diamonds) transmission systems.

equal to -18 dBm at the receiver. The remaining components in Fig. 2 are equal to those in Fig. 1 and have the same functionality.

Both experimental setups of Fig. 1 and 2 are characterized by a phase error standard deviation of almost 5 degrees. The effect of such an error on the system performance is negligible [9]. Furthermore, the signal power at the receivers input is such that the ASE noise is the only impairment that influences the performance results presented in the following section.

III. Experimental results

Performance of the presented transmission systems were investigated trough bit error rate (BER) measurements. Fig. 4 shows the BER against the OSNR measured for the 2.5 Gbps ASK and PSK transmission systems of Fig. 1 and 2. The same figure also shows a curve obtained by an intensity modulation direct detection (IM-DD) system that is derived by replacing the coherent receiver (Fig. 2) with a 2.5 Gbps amplified photodiode. We measured 10^{-9} BER for OSNR values of 10.5 dB (PSK), 115 dB (ASK) and 12.5 dB (IMDD). A comparison between the three systems shows best performance of the PSK system as expected, which demonstrates a gain of 1 dB with respect to the ASK system and almost 2 dB with respect to the IM-DD system.

The PSK transmission system was also tested with a 10 Gbps bit rate. Fig. 5 shows the measurement results expressed as Q factor versus the OSNR, along with the eyediagrams corresponding to a Q of almost 16 dB (BER = 10^{-10}). Also in this case, the performance of the PSK system is compared with an equivalent IM-DD transmission system. BER of 10^{-9} was measured for values of OSNR equal to 13.5 dB (PSK) and 17.5 dB (IMDD). The PSK transmission system presents better performance and Fig. 4 shows almost 4 dB of gain.

IV. Conclusion

In summary, we have demonstrated homodyne detection of PSK and ASK signals using an optical phase-locked loop based on sub-carrier modulation. All the components we used are commercially available today, thus demonstrating the technical feasibility of coherent homodyne detection by means of compact integrated receivers.

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