

New Opportunities for Optical Phase-locked Loops in Coherent Photonics

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Abstract: New efforts demonstrate that integrated optical phase-locked loops can provide stable and robust phase locking. Coherent receivers now use DSP processing for long haul communications. However, given a low-cost, low-power coherent receiver, uses in shorter links become viable, and other approaches for removing impairments can be explored.

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1. Introduction

As fiber optic communication developed through the 1970s and into the early 1980s, link distances increased to tens of kilometers and single-channel bandwidths toward the Gb/s range, as single-mode fiber and 1300 nm wavelength InGaAsP/InP-based materials became the norm for such ‘long-distance, ‘high-capacity’ communication. To increase capacity, a few wavelengths could be multiplexed onto a single fiber, although this was not very common. Every 30 km or so, these directly-modulated channels had to be (demuxed if WDM), received by a photodetector-preamp, 3-R regenerated in the electrical domain, and remodulated back onto a lightwave, (and muxed if WDM) for further optical transmission. The switch to 1550 nm aided the loss budget by almost a factor of two, but dispersion was added and now had to be dealt with by using well-engineered external modulation.

To improve the reach between such repeaters, coherent receivers, which could vastly improve the sensitivity, and thus the repeater spacing, were intensively explored throughout the 1980s [1-8]. With the highest sensitivity, homodyne phase-shift-keying (PSK) receivers were well studied, and several prototypes were demonstrated with very high sensitivity [1,3-5,7,8]. However, theoretical studies showed that because of the shot noise limit and the limited optical phase-locked loop (OPLL) bandwidth, these homodyne PSK receivers had a high requirement on the LO laser linewidth [3,6,9]. Moreover, the limited loop bandwidth also placed a stringent requirement on system stability [5]. Any small temperature change of the LO laser or other environment fluctuations may cause the OPLL to lose lock. Therefore, there were no commercial products based on OPLLs, as they were seen as being very difficult to use, and perhaps costly and unreliable.

The interest in coherent receivers and PSK modulation dropped greatly after the invention of the erbium-doped fiber amplifier (EDFA), and also as wavelength division multiplexing (WDM) technology became more mature in the 1990s. With this, many optical channels of different wavelengths could be multiplexed onto a single fiber, and they could be amplified all together within the fiber after some nominal distance without any need for the conversion into the electrical domain for regeneration. This was much more cost effective for long-haul, high-capacity networks. Dense WDM/EDFA capacity has grown exponentially, first very rapidly in the 1990s, and more slowly since about 2002 [10], the slow-down being initially associated with the burst of the ‘tech bubble.’

However, more recently, since about 2008, coherent detection has returned, not so much because of enhanced sensitivity, but because of the *spectral efficiency* that it can provide when the full vector optical field is detected. It turns out that we really were about to run out of fiber bandwidth, as many claimed around 1998, it just didn’t happen until a decade later! Of course, coherent detection is complementary to WDM/EDFA transmission systems, but it enables a higher data rate without using a higher fundamental baud rate. Thus, issues like fiber dispersion and other impairments can be lessened, even as the link capacity is enhanced.

Optical phase-locked loops (OPLLs) are still not widely used in communication, although they continue to be used in some sensor applications, for the reasons mentioned above. Intradynic techniques, which use high-speed ADCs and sophisticated digital-signal-processors (DSPs) dominate the long-distance communications field [1,10]. By applying complicated algorithms, most of the linear and nonlinear effects introduced by the long-distance propagation can be eliminated, and multiple-phase as well as multiple-level two-dimensional modulation formats

can be achieved, such as QPSK, 16QAM, and 256 QAM [9-12]. Unfortunately, such intradyne systems tend to be very costly to design, fabricate and operate, given the market quantities involved, and they consume a lot of power. They do not appear to be very competitive for the emerging higher-volume, shorter-link markets in data centers, high-performance computing, and high-capacity metro-links where spectral efficiency, and oftentimes fiber cable volume, are becoming key issues [13].

In this paper we will briefly review some of the past work, and then discuss some more recent efforts to make much more stable OPLLs that are also small in size, low in required power, have virtually no latency, and should be low in cost to produce, even in modest volumes. Although research on OPLLs has continued [14-17], the loop bandwidth problem had not been fundamentally solved until the work of the authors [18-22]. Also, relatively simple, but elegant, custom electronic ICs have been designed to solve many of the other stability issues [20,22]. Unlike the homodyne PSK receivers of the 1980s, advanced integration technologies were used for these OPLLs to make the system very compact and much more stable. 40 Gbit/s data rate has been achieved [20]. Compared to intradyne, this OPLL system has a much simpler architecture, and consumes much less power. Although it may suffer from fiber impairment issues for long haul communications, this is probably not its primary target market. Compared to OOK systems, this OPLL-based receiver retains the inherent highest available sensitivity as a homodyne PSK receiver, which provides for the maximum link reach [23]. The frequency/phase locking function in this OPLL also prevents channel wavelength drift due to temperature or aging, and this can enable many new system capabilities such as a dense (25 GHz spacing) WDM PON system [24] for example.

2. Homodyne receiver with an OPLL

The homodyne receivers that have been proposed by the authors is based on the classic Costas loop structure [20], which includes an optical I/Q receiver including an LO laser, a phase/frequency detector (PFD), and a loop filter. The architecture of this OPLL is shown in Fig. 1.

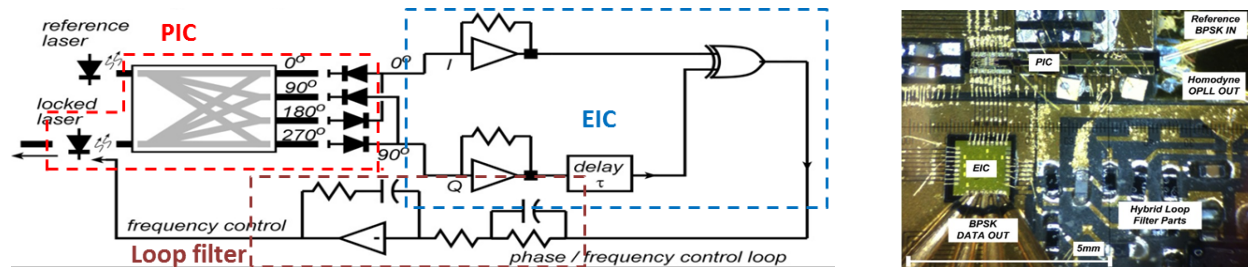


Fig. 1. (a) The architecture of the homodyne receiver. (b) A microscope picture of the receiver (mostly dominated by the discrete loop filter).

As shown, it is composed of a photonic integrated circuit (PIC) [20], an electronic integrated circuit (EIC), and a loop filter (LF). The PIC is a commonly used coherent circuit, including a widely-tunable SG-DBR laser as the LO laser, a 90 degree hybrid, and four high-speed uni-travelling-carrier (UTC) photodetectors (PDs). The detected I/Q signals are fed back to the LO laser phase-tuning section by current injection. Fast feedback tuning can be achieved. The EIC includes limiting amplifiers as the front-end, and a quadri-correlator as the PFD. The discrete LF is used to introduce more gain and stabilize the loop. The EIC and LF potentially can be integrated on a single CMOS ASIC with relatively low cost.

The system is built within a $10 \times 10 \text{ mm}^2$ carrier, and the phase locking is achieved with 1.1 GHz closed loop bandwidth. The system testing setup is shown in Fig. 2(a), and the BER vs OSNR results are shown in Fig. 2(b) as well as the eye diagram.

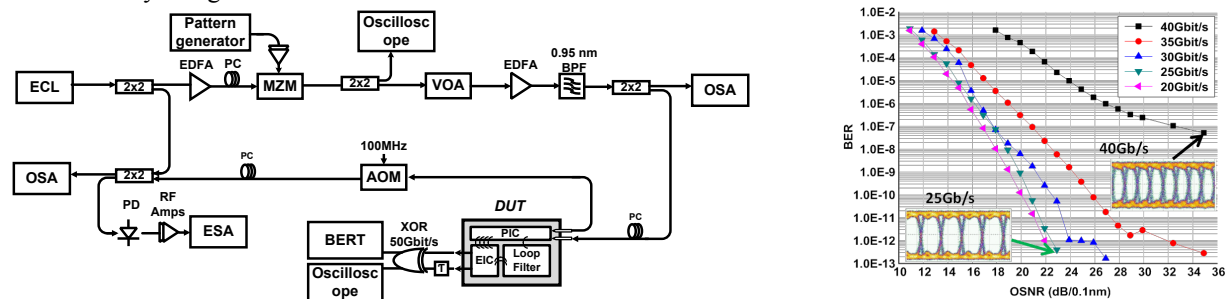


Fig. 2. (a) The test setup for the homodyne receiver testing. (b) BER vs OSNR from 25 Gbit/s to 40 Gbit/s. The eye diagrams are also shown.

Compared to previous efforts on homodyne receivers, this integrated OPLL receiver shows very high data rate and low BER at the same time. The integration ensures wider loop bandwidth, which leads to superior system stability and more flexibility with the LO linewidth. (The free-running widely-tunable LO linewidth is more than 10 MHz in this experiment, but it duplicates that of the signal carrier once locked—here $\sim 100\text{kHz}$.)

3. Heterodyne transmitter with an OPLL

By using a similar architecture and integration platform, a heterodyne OPLL has also been demonstrated [17]. Compared to the homodyne OPLL shown in Section 2, the heterodyne OPLL includes a single-sideband mixer (SSBM) in the EIC, which introduces the desired single-sideband frequency shift. Offset locking can be achieved with an offset frequency ranging over about 40 GHz. Since PFD is integrated, continuous phase-locked frequency sweeping can be achieved by *only* tuning the RF synthesizer frequency. The system is also very stable, and the phase error variance has been measured to be $< 0.03 \text{ rad}^2$, integrating from 100 Hz to 10 GHz.

4. Conclusions

The reasons why the OPLL-based homodyne receivers are not currently used are mainly because i) the homodyne receiver has the most stringent requirement on linewidth [4,9], and ii) the limited bandwidth also makes the loop hard to be stable. However, as we have shown, photonic and electronic integration changes the situation. Since loop bandwidth is increased by orders of magnitude compared to early homodyne, the OPLL works and the data rate also goes up by orders of magnitude; thus, the homodyne receiver becomes viable for real communication systems. The advantages of higher receiver sensitivity remain. Although the removal of long-haul impairments still remain at issue, integrated OPLL-based receivers would appear to offer many advantages for shorter distance links where such impairments are not a big issue. The power dissipation is low, the footprint is low, and the cost should also be low.

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