OPTICAL PHASE-LOCKING AND WAVELENGTH SYNTHESIS

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Abstract —**We describe techniques for phase-locked coherent optical communications, including wavelength synthesis for wavelength-division-multiplexed optical communications, compact coherent BPSK receivers, and coherent demodulation of WDM in the electrical domain.**

Index Terms — Coherent optical communications, phase-locked-loops, frequency synthesis, wavelength-division-multiplexing

I. INTRODUCTION:

Prior to the widespread adoption of phase-locked loop frequency synthesizers [1], transmitter carrier frequencies and receiver tuning frequencies in RF/microwave systems were widely set by simple resonators, whether *LC*, quartz, or waveguide. Radio channels were spaced widely to accommodate frequency variabilities. To select stations, receivers were manually, mechanically tuned. This might have been by the user, as in an AM or FM radio. In TV sets, fine channel tuning was set by trimming capacitors, adjusted first in the factory and again in the TV repair shop. Compact monolithic phase-locked frequency synthesizers (Figure 1) entered widespread use in the late 1970's and early 1980's. These enabled radio transmit and receive frequencies to be precisely set, and readily tuned under digital control, with frequency precision set by a single quartz-crystal reference oscillator. Frequency synthesizers enabled precision phase and frequency control and efficient use of the radio spectrum, and eliminated frequency drift, making receivers much more reliable.

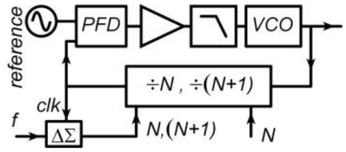
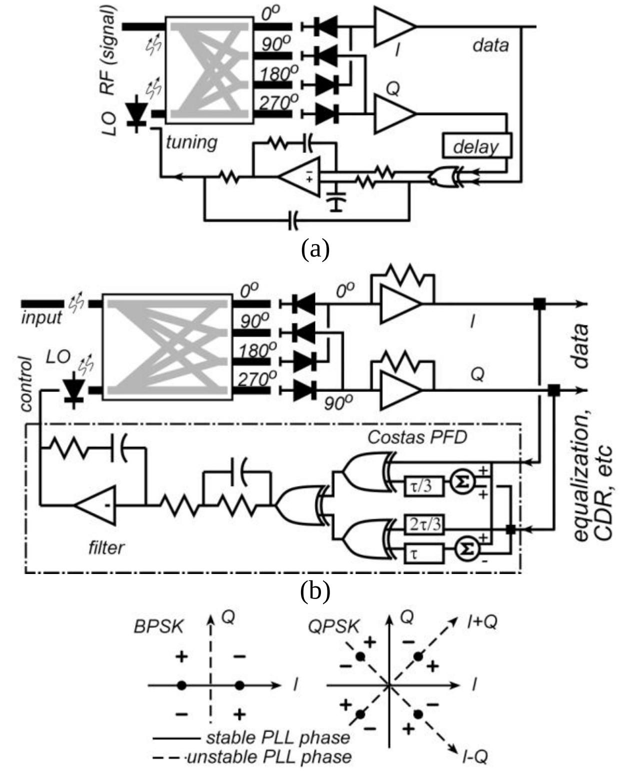


Figure 1: Frequency synthesizers set transmit and receive frequencies in most RF/microwave systems.

Signal frequency control in today's optical systems resembles that of pre-1970's RF/wireless systems. In wavelength-division multiplexed (WDM) links [2], channel frequencies and spacings are controlled by sets of optical resonators [3], while receivers separate wavelength channels using optical filters [4]. To accommodate laser and filter tuning errors, channel spacings must exceed modulation bandwidths. This impairs spectral efficiency, a consideration of increasing concern as optical links approach the fiber capacity [5].



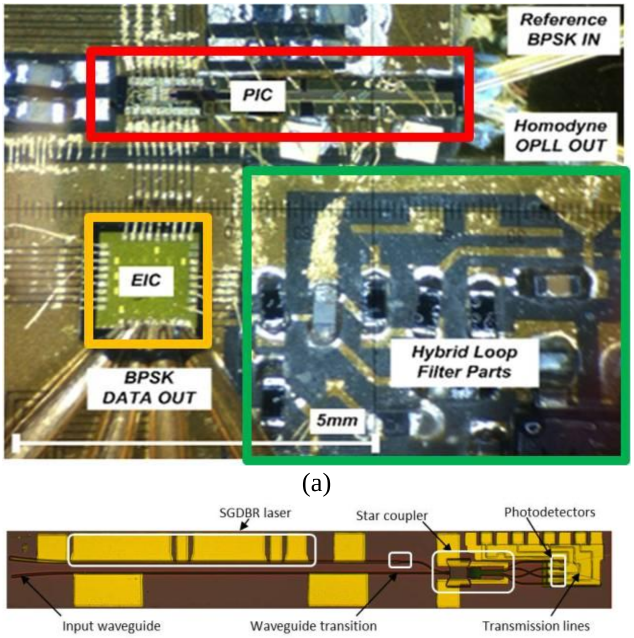
(a)

(b)

(c)

Figure 2: Optical phase lock loop (a) and BPSK receiver. Coherent receiver (b) with QPSK Costas phase detector. phase detector output polarity (c) and stable PLL lock points superimposed on the BPSK (left) and QPSK (right) constellations.

Using optical phase-lock-loops (OPLLs) and wavelength synthesis, optical signal frequency spacings can be set precisely under digital control. This will enable sensitive, compact, spectrally efficient, optical communications. OPLL applications include wideband laser phase-locking to improved laser spectral purity without external optical cavities. OPLLs will enable BPSK/QPSK coherent receivers; these will serve short- to mid-range links, will use inexpensive wide-linewidth lasers, and do not require fast DSP for optical carrier recovery. OPPLs will enable tunable wavelength-selection in optical receivers, permitting electronic channel selection for WDM. OPLLs will enable electronic wavelength tuning and sweeping, and generation WDM channel combs, all under digital control. Finally, together with modern wideband electronics, OPLLs enable *electrical* demodulation of WDM, enabling compact single-chip multi-wavelength coherent receivers



(a)

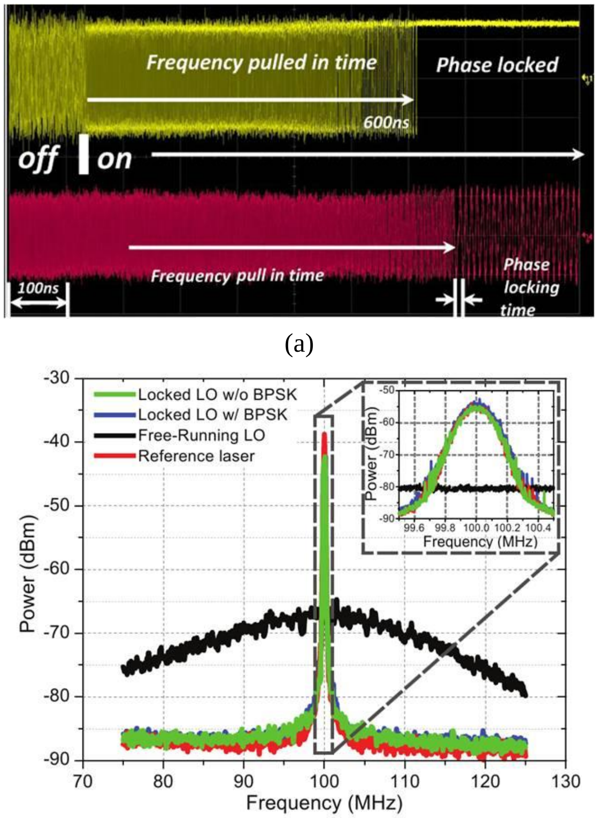
(b)

Figure 3: Optical PLL (a) showing the photonic IC (PIC), electrical IC (EIC), and hybrid loop filter, and (b) the PIC, incorporating tunable SGDBR laser, star coupler, and detectors.

II. OPLL DESIGN

In an OPLL [6,7] (Figure 2a) an LO laser is phase-locked to a stable reference laser or to a received signal. The phase detector, an optical mixer, is a photodiode illuminated by the LO and reference (RF) lasers. The loop has gain and a filter, and the LO laser a frequency tuning electrode [8]. If the reference has narrow linewidth (low phase noise), then phase-locking the LO laser will improve its linewidth. If we are to use inexpensive lasers lacking external optical cavities for linewidth suppression, then ~1 GHz OPLL loop bandwidth is required. Optical and electrical path lengths must be small, forcing tight (~5 mm) dimensions.

A 1.55 μm laser oscillates at 194THz; upon turn-on the LO and RF lasers may be initially offset by as much as 20GHz. With a maximum ~1GHz loop bandwidth set by path lengths and LO laser tuning dynamics, the initial frequency offset far exceeds the loop bandwidth and an OPLL with a simple phase detector will not reliably acquire lock. To ensure that the OPLL reliably locks, it is equipped (Figure 2a) with a Costas phase-*frequency* difference detector constructed from a quadrature (I,Q) optical mixer, delay stage, and electrical mixer (XOR gate). The (I,Q) mixing maintains, within the loop bandwidth, the full optical field information, enabling BPSK/QPSK receivers, wavelength synthesizers, and optical/electrical SSB mixers for electrical WDM receivers..



(a)

(b)

Figure 4: Phase-locked BPSK receiver. Locking transient (a) showing 600ns frequency acquisition and ~10ns phase-acquisition times. The yellow trace is the Q output, while red trace is the transmitter/receiver laser beat note, offset by 100MHz. Beat note (b) between the transmitter & receiver lasers, showing LO laser phase noise suppression.

III. PHASE-LOCKED BPSK/QPSK RECEIVERS

In a phase-locked receiver, an OPLL synchronizes the LO laser to the received modulated data stream. The phase detector output must not vary with the data modulation. OPLLs having Costas phase detectors appropriate for BPSK and QPSK are shown in Figure 2; the phase detector characteristics are also shown (Figure 2c). We have demonstrated coherent phase-locked coherent receivers [9]; Figure 3 shows the assembly and the photonic ICs [8]; the electrical ICs [10] are ECL, using Teledyne's 500nm, 350GHz-(f_τ , f_{max}) InP HBT process. The frequency difference detector functions over +/-40GHz [10]. The OPLL acquires frequency lock in 600 ns (Figure 4a) and phase-lock in 10 ns. The loop greatly suppresses (Figure 4b) the LO laser phase noise. The receivers operate to 35Gb/s, and are sensitive (Figure 5)

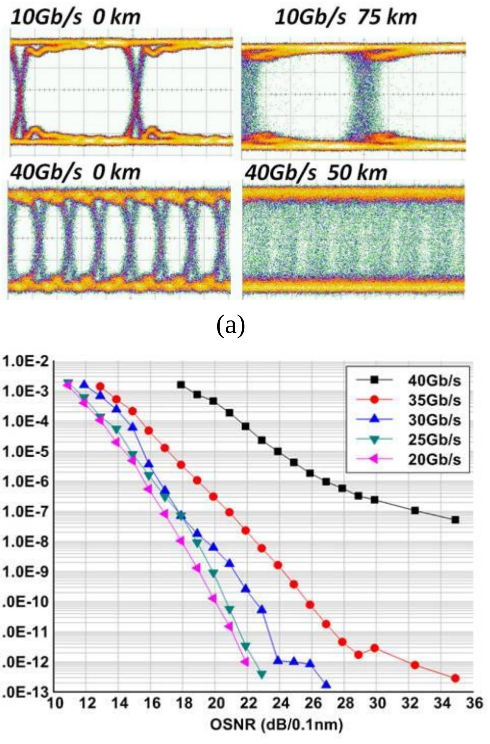


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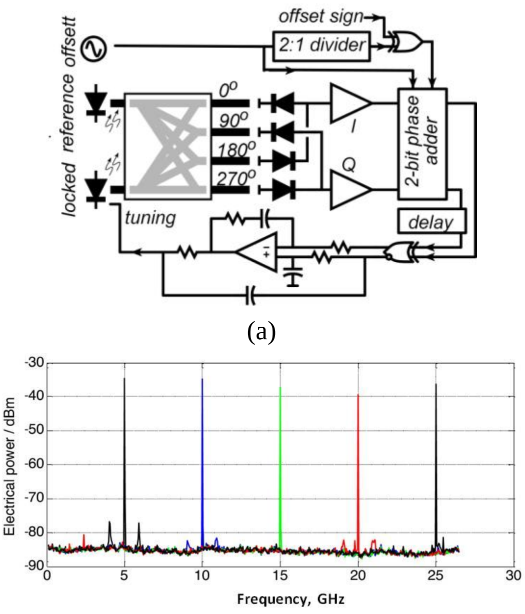
Figure 5: Phase-locked BPSK receiver output (a) at various data rates and transmission ranges and (b) receiver error rate.



(a)

(b)

Figure 6: Optical wavelength synthesis: block diagram (a) showing loop with 2-bit digital single-sideband frequency mixing. Measurement (b) of OPPL laser frequency tuning over a 20GHz range.

IV. Optical Wavelength Synthesis

Similar to an RF/microwave synthesizer, OPLLs can generate precise optical frequency spacings. Unlike an RF/microwave [1] synthesizer (Figure 1), OPLL frequency ratios cannot be scaled by counting optical cycles; instead (Figure 6a) the laser frequency is swept by introducing, by a mixer, a frequency offset into the loop. To control without ambiguity the sign of this introduced frequency offset, a single-sideband (SSB) mixer must be employed, which demands (*I*,*Q*) quadrature optical mixing. The SSB mixer is digital (Figure 6a), with the optical beat note represented with 2-bit precision and added in phase to that of the frequency offset signal [10].

Figure 6a shows the wavelength synthesizer tuning from 5GHz to 25GHz offset. There are four phase additions for each cycle of the offset signal. By cascading (Figure 7) such offset-frequency OPLLs, sets of WDM carrier wavelengths can be precisely generated and tuned.

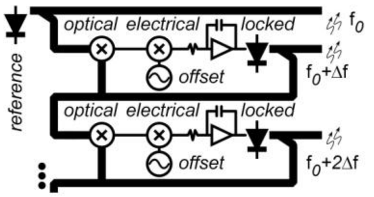
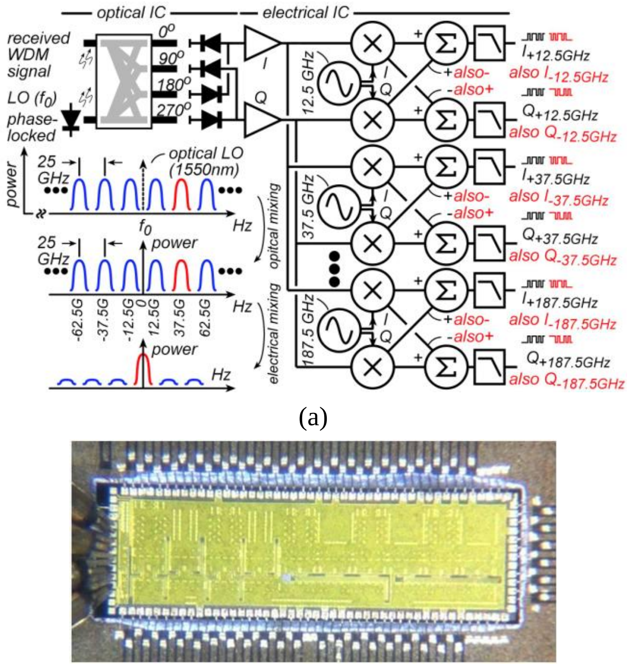


Figure 7: Synthesis, by offset OPLLs, of channel spacings within wavelength-multiplexed optical communications.



(a)

(b)

Figure 8: Receiver for demodulation of optical wavelength-division-multiplexing demodulation in the electrical domain; block diagram (a) and die photograph of prototype six-channel receiver (b) in a 500nm InP HBT technology.

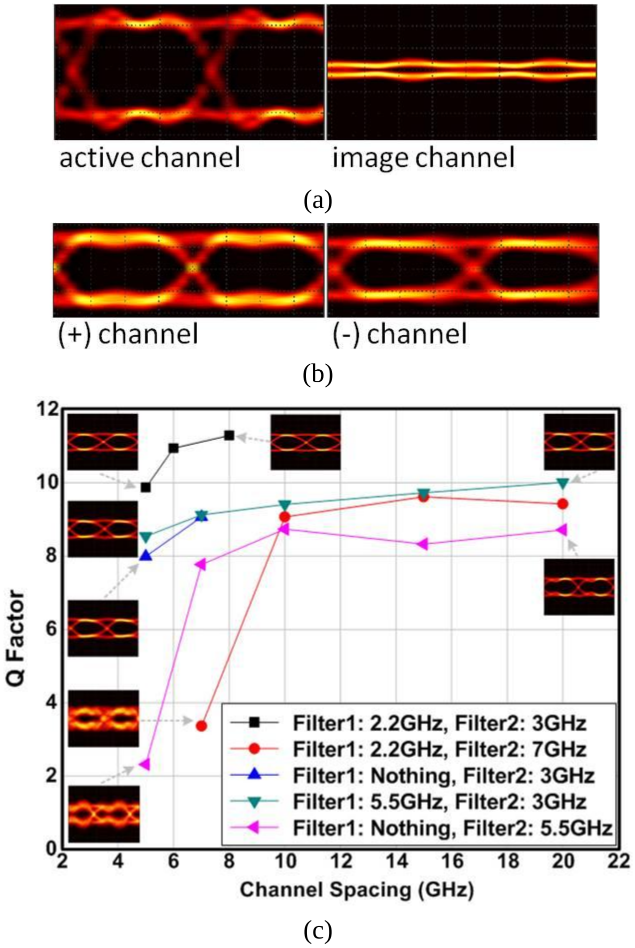


Figure 9: Electrical WDM receiver tests. Image-wavelength rejection tests showing rejection (a) of the image channel and (b) interference-free eye patterns when both image channels operated. Adjacent-channel (c) rejection tests showing high Q, i.e. signal/(interference+noise), even with optical channels carrying 2.5 Gb/s BPSK at 5 GHz spacing.

IV. ELECTRONIC WAVELENGTH- DEMULTIPLEXING

In coherent receivers, WDM signals can be demultiplexed electrically [11] (Figure 8), replacing many WDM receivers with one PIC and one electrical IC. WDM signals at 25GHz separation first become electrical subcarriers at 25GHz separation, and then are downconverted to DC using a cascade of (I,Q) optical and microwave mixers in a Weaver single-sideband configuration. With modern THz InP HBT processes [12], IC bandwidths can exceed 600 GHz [13], hence in principle one such electrical IC might recover 48 WDM channels at 25 GHz channel spacing. In a SiGe BiCMOS process, >200GHz electrical IC bandwidths are feasible today, and the receiver of Figure 8 could recover 16 WDM channels at 25GHz spacing. Such a design would eliminate the receiver WDM optical filter bank, the multiple LO lasers, and the multiple electrical receivers presently used in a WDM coherent receiver array.

We have fabricated both 2-channel [11] and 6-channel (Figure 8b) WDM electrical receivers incorporating the SSB frequency conversion but omitting the baseband signal processing. In tests of the two-channel receiver, both SSB image-wavelength channel (Figure 9a) and adjacent-wavelength channel rejection tests (Figure 9b) show minimal crosstalk between channels in the WDM receiver.

The present ICs used 50Ω interconnects and ECL design techniques throughout, and have very high power consumption. Power might be saved using CMOS mixer arrays using analog FFT techniques [14] and charge-steering logic [15]. If an optical pilot is transmitted, the receiver can phase-lock even given high optical dispersion; further, it may be possible in this receiver to compensate for fiber dispersion using analog filters at baseband, thus avoiding the power consumption of DSP. Total DC power relative to WDM receivers using back-end DSP [5] will determine feasibility.

ACKNOWLEDGMENT

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