Optical Carrier Recovery Using Feedforward Phase Compensation

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Abstract *We present theoretical analysis and experimental demonstration of optical carrier recovery using Feedforward Phase Compensation for the first time. The measured phase error is estimated less than 0.05 radian*

Introduction

There is resurgence of research interests in coherent keyed system such as differential-phase-shift-keying (DPSK) because it offers a 3 dB OSNR advantage over conventional On/Off keying [1-2]. PSK offers potential another 3 dB improvement [3], but complexity and cost of the coherent detection system hinder its practical application. It would be desirable to use commercial semiconductor lasers for such a system [4]. However the optical phase lock loop (PLL) bandwidth needs to be from several tens of MHz to several hundreds of MHz. Such a high-bandwidth PLL becomes unstable due to finite physical delay of the circuit [5]. In this paper, for the first time we propose a novel optical carrier recovery method using Feedforward Phase Compensation (FPC) to resolve the stability of the phase recovery. We first provide theoretical analysis of the principle, and find that the FPC bandwidth can be arbitrary large as far as the stability is concerned, and is only limited by the system phase error requirement. Additionally we perform an experiment to prove the concept and show that the phase error of the recovered carrier is less than 0.05 radian.

Principle of FPC

Fig. 1 shows the principle of the FPC. The local oscillator (LO) laser is frequency off-set f Hz from the incoming signal laser. A part of the LO and incoming signal are combined and detected by a photodiode. If we assume fields of $\sqrt{P_{Lo,s}}e^{i(\omega_{Lo,s}\cdot t+\phi_{Lo,s})}$ for the signal and LO, where P is the power, ω is the angle frequency and ϕ is the phase, the detected photocurrent is

$$I \propto P_{Lo} + P_s + 2\sqrt{P_{Lo}\cdot P_s}\cos(2\pi f + \Delta\phi) \quad (1)$$

where $\Delta\phi = \phi_{L0} - \phi_s$ is the phase difference between LO and signal. The detected current is converted to an RF signal, passed through a RF filter centered around f Hz, amplified and fed into optical modulator to amplitude modulate a delay-matched LO component. The RF amplification is operated in deep saturation nonlinear region to remove the amplitude fluctuation while maintaining the phase noise integrity. The optical field at the output of the modulator shows a spectrum of multiple harmonics spacing at f Hz. Particularly one of the first harmonic (n=-1) is of interest, and can be shown to have an amplitude E_{-1} give by [6]:

$$E_{-1} \propto e^{(i\omega_s t+\phi_s)}\cdot J_1(\pi A/V_\pi)\cdot\sin(\phi_0/2) \quad (2)$$

where $J_1(x)$ is the first-order Bessel function, ϕ_0 is the phase offset of the two arms of the modulator, and A is half peak-to-peak of the RF drive voltage. We can see that this first harmonic shares the same phase with the signal and therefore perfect phase recovery is achieved. The matched delay for the LO path is assumed for the derivation. If the offset frequency is large enough, e.g., 10 GHz beyond, the carrier recovered LO can be optically filtered out. Furthermore, because the other harmonics are either far from the signal or too weak, it will be naturally filtered out by the receiver electrical filter without need for an optical filter. A similar FPC was proposed for photo-mixing of two laser diodes for Millimeter wave application with a focus on the RF spectral purity [7]. The laser frequency offset arrangement and optical modulation is also similarly shown by Ref. 8 as an extension of PLL. We differ in the novel FPC approach to the optical carrier recovery and related phase error analysis and measurement.

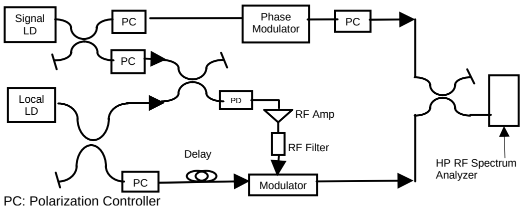

Figure 1: Conceptual Diagram of FPC

The phase error $\Delta\phi$ of the FPC technique can be shown consisting of the three sources:

$$\Delta\phi^2 = \Delta\phi_d^2 + \Delta\phi_r^2 + \Delta\phi_s^2 \quad (3)$$

where $\Delta\phi_d$, $\Delta\phi_r$ and $\Delta\phi_s$ are the phase errors due to delay mismatch, finite FPC phase noise bandwidth, and the FPC system noise respectively. It can be shown that

$$\Delta\phi_d^2 = 2\pi B_{LO}\tau_{LO} + 2\pi B_S\tau_S,\ \Delta\phi_r^2 = 2B_t/(\pi B_e) \quad (4)$$
$$\Delta\phi_s^2 = m^{-1}\cdot[1/(2\cdot OSNR\cdot\Delta\upsilon) + e/(2R\cdot P_s)]\cdot B_n$$

where $\tau_{LO,S}$ ($B_{LO,S}$) is the delay mismatch (linewidth) of signal or LO path, B_e is the phase noise bandwidth, B_t is the total linewidth of the signal and LO equal to the sum of their linewidth, m is the power ratio of the unsuppressed optical carrier being recovered, OSNR is the optical Signal-to-Noise Ratio of the signal due to Amplified Spontaneous Noise (ASE), $\Delta\upsilon$ is the noise bandwidth of ASE for the OSNR measurements (e.g., 12.5 GHz if 0.1 nm used at 1.55 μm), R is the responsivity of the receiver, e is the electronic charge, and P_s is the signal power. The Relative-Intensity-Noise (RIN) of the LO is ignored in the analysis. Compared to the theory of the PLL, the phase error of FPC has an explicit contribution due to delay mismatch and a different definition of B_e because the nonlinear nature of the limiting amplifier in FPC. For deep limiting amplifier which output only '0's and '1's, we expect it to be the bandwidth of the RF filter. B_e can be best obtained by measurement. B_n is the bandwidth of the noise equal to the filter bandwidth. A practical implementation of this FPC could be done through Photonic Integrated Circuits (PIC), where delay mismatch can be performed with accuracy of 1mm. From Eq. 4, we have phase error $\Delta\phi_d$ of 0.06 radian for a laser linewidth of 100 MHz whereas PLL is problematic for stability of this order [5].

Experiment and Results

The experimental setup we put together to demonstrate the concept is shown in Figure 1. Both signal and LO laser diodes (LD) are Photonetics ECL lasers with a frequency offset of 10 GHz. Each LD is optically split with one branch fed into the FPC circuit, and the other fed into a phase noise characterization setup. The RF filter in FPC is centered at 10 GHz with 50 MHz 3 dB bandwidth. The RF amplitude limiting is performed by a limiting amplifier integrated with the photodiode (PD) and the optical modulator driver. The second branch of the signal and LO are combined and fed into an HP RF analyzer with an optical feed for phase noise characterization. The composite linewidth of the two lasers are measured to be 50 KHz. We make no extreme effort to match the delay and leave it to further research for Photonic Integrated Circuits (PIC) implementation. The phase coherence/incoherence is characterized by either modulating the signal phase with a phase modulator or detecting the low frequency noise of the beating between the signal and carrier recovered LO.

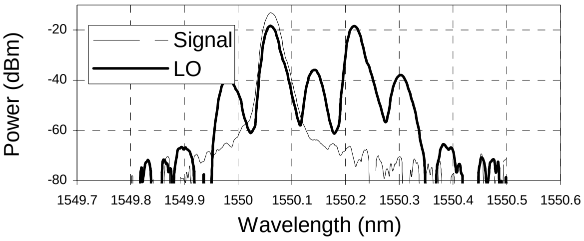

Figure 2: Optical Spectrum of the signal laser and LO into the RF spectrum analyzer

Figure 2 shows the optical spectrum of the signal laser and carrier recovered LO. We can see that the signal spectrum matches with one of the first harmonics of carrier-recovered LO as predicted by the theory. To simply measure the low frequency noise of beating between the signal and carrier recovered LO is not convincing proof of phase coherence. This is because the signal and LO is offset at 10 GHz with FPC off, the beating of these two lasers with no coherence produces no noise at low frequency, which might be mistaken as low noise from high coherence. To first show the coherence between the recovered carrier and signal, we modulate the signal path with a phase modulator at 500 MHz. Figure 3 shows the detected modulation at 500 MHz. In comparison, we show the RF spectrum in the same figure when the FPC is off by turning off the RF amplifier in the FPC circuit. We observe almost no RF modulation at 500 MHz due to lack of coherence between signal and LO. Because of the drift from lengthy fibers along each path including many couplers, patch cords and modulator pigtails, it is difficult to hold the two paths in quardrature. Therefore the RF signal and noise spectrum can be considered to be time averaging result. Since any phase/frequency error of the carrier recovery will directly translated into this RF signal, we try to identify the linewidth of the 500 MHz signal and find that it is less than 10 Hz only limited by the resolution of the RF spectrum analyzer. We measure the phase noise at low frequency noise below 50 MHz from beating of the signal and LO, and find the phase error is less than 0.05 radian excluding the contribution from the delay mismatch and the phase drift of the fiber due to thermal and acoustic effects. For the reference, the phase error of 0.2 radian is required to achieve BER of 10^{-9} for a PSK system [5].

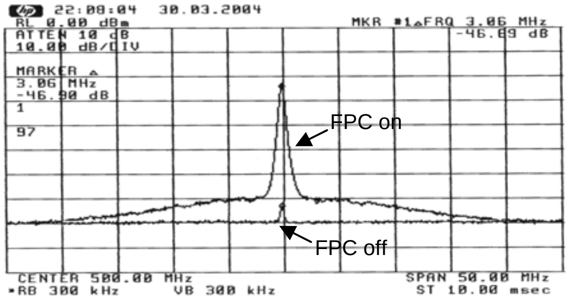

Figure 3: The RF spectrum with FPC on and off

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