Bio-Inspired Optical Microwave Phase Lock Loop based on Nonlinear Effects in Semiconductor Optical Amplifier

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Abstract: *Optical microwave phase lock loop using semiconductor optical amplifiers is experimentally demonstrated. Bio-inspired by Eigenmannia and implemented with photonics, the proposed scheme is compact, has a simple architecture, and has a wide operating frequency range.*

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1. Introduction

Microwave phase lock loop (PLL) is the core component for frequency and phase synchronization between subsystems, and has been gaining attention by researcher and industry due to its wide range of applications, such as radar systems, wireless communications, software defined radios, and modern instrumentations [1]. A typical microwave PLL consisting of a phase detector and a feedback controller, such that the target oscillator can maintain a constant phase relative to a reference signal. In electrical approaches, phase detection is usually achieved using a frequency double-balanced mixer (DBM), which the mixer output represents the phase difference between the two inputs. However, phase detection performance is limited by the circuit imbalance in the mixer. Furthermore, the DBM has to be saturated for phase detection, which essentially shrinks its bandwidth and requires strong input power [2]. Tuning to photonics for a solution, recently a balanced optical-microwave phase detector has been demonstrated as a microwave PLL [3,4], which can be used for optical-RF extraction with sub-fs absolute timing jitter. The approach, however, is a rather complex system that involves a large number of components, which may not be a compact and cost effective solution for most applications.

In this paper, we present a photonic-based microwave phase lock loop that is inspired by the jamming avoidance response (JAR) neural circuitry of the Eigenmannia, a genus of electrical fish [5]. In JAR, Eigenmannia is able to determine the frequency difference sign between its own emission frequency and a nearby Eigenmannia's emission frequency for jamming avoidance. The Eigenmannia achieves this neural response by evaluating modulations of the instantaneous phase and amplitude relationship with the nearby sinusoidal signal from another fish. In the JAR, a phase detector is used to determine any phase lead or phase lag between its own emission frequency and the beating signal with the nearby fish. Our work borrows the algorithm of this neural phase detector from the JAR and implements it using optical nonlinearity in semiconductor optical amplifier (SOA), for detecting the phase difference between the reference signal and a local voltage controlled oscillator (VCO) in a microwave PLL. The use of SOA provides a compact and cost efficient photonic approach for implementing wideband phase lock loop.

2. Principle, Experimental Setup and Results

Principle of phase detection in the JAR neural circuitry is shown in Fig. 1(a). In JAR, phase detection is performed between the Eigenammia signal and a beat signal (beat signal between the jamming signal and the Eigenmannia). When we have an Eigenmannia discharging a sinusoidal signal (f_E) at 100 MHz for example (dashed blue curve in Fig. 1(a)) that beats with an 80 MHz interference sinusoidal signal (f_I), the resultant beat signal will have an envelope at 20 MHz (solid red curve in Fig. 1(a)). The peaks of the beat signal travel around the peaks of the Eigenmannia signal, indicated by grey solid circles in Fig. 1(a), which shows that the phase difference between the Eigenmannia signal and the beat signal experiences a periodic change. If we use the positive zero crossing points of the Eigenmannia signal as a reference, indicated by the green arrows, then a positive amplitude in the beat signal

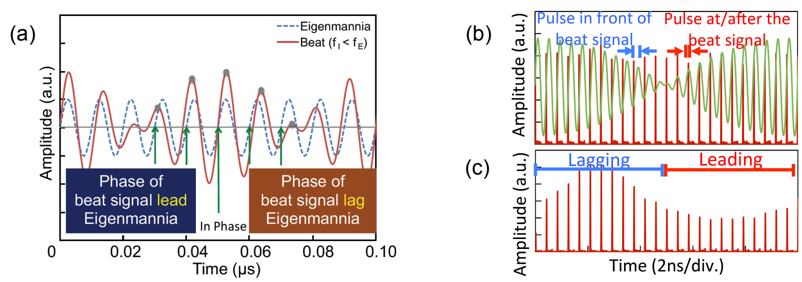

Fig. 1. (a) Principle of phase detection in JAR neural circuitry. (b) Input signals to phase detector (c) Output of phase detector.

corresponds to a phase lead, while a negative amplitude corresponds to a phase lag. Therefore, phase lead/lag can be determined by examining the amplitude of the beat signal at each positive zero crossing points. Fig. 1(b) shows a simulation of the relationship between phase difference and the resultant amplitude information from the JAR. i.e. a low intensity corresponds to phase leading, while high intensity corresponds to phase lagging. Same principle can be applied when comparing phase difference between two sinusoidal signals. This bio-inspired phase detector will be used in the optical microwave PLL that we are proposing here.

The experimental setup for the proposed optical microwave phase lock loop is shown in Fig. 2. The sinusoidal signal generated from a signal generator acts as the reference signal at the frequency of f_R, which has good long term stability in terms of amplitude and phase. The reference signal is launched to a frequency divider, where the sinusoidal signal is transformed and divided into a square signal at 1/8 of f_R (Fig. 2(a)). The phase detection starts by modulating the square signal onto an optical carrier from a distributed feedback laser with wavelength at 1549.27 nm using an electro-optic intensity modulator (EOM1). The modulated optical signal is amplified to 8 dBm before launching into SOA1 for positive zero crossing point extraction. In SOA1, self-phase modulation occurs and leads to optical spectral broadening in the signal, as shown in Fig. 2(b). The optical spectrum shifts to longer wavelength at the raising edge of the square wave, while it shifts to the shorter wavelength during the falling edge. Therefore, by properly selecting the longer wavelength portion of the spectral broadened spectrum (Fig. 2(c)) using an optical bandpass filter (BPF1), the positive zero crossing points of the square wave (at 1/8 of f_R) is extracted. The optical bandpass filter has a 3-dB bandwidth of 0.1 nm, pulses at the frequency of $f_R/8$ are obtained, as shown in Fig. 2(d).

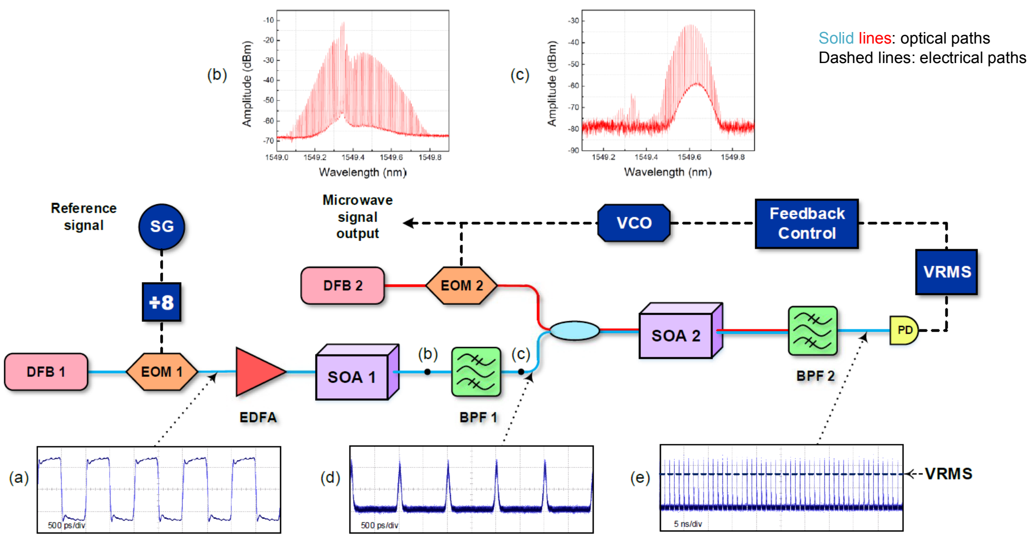

Fig. 2. Experimental setup of the proposed optical microwave phase lock loop. SG: signal generator; DFB1-2: distributed feedback laser diodes; EOM1-2: electro-optic intensity modulators; EDFA: erbium-doped fiber amplifier; SOA1-2: semiconductor optical amplifier; BPF1-2: optical bandpass filter; PD: photodiode; VCO: voltage controlled oscillator; VRMS: root mean square voltage detector.

Initially, the VCO is operating at roughly the same frequency as the reference signal. 50% of the VCO sinusoidal output is modulated onto an optical carrier from a second distributed feedback laser with wavelength at 1533.33 nm through EOM2. The sinusoidal-modulated optical signal is then combined with the positive zero crossing point pulses and launched to a second SOA. The sinusoidal-modulated signal acts as the pump light in the SOA with an optical power of 6.5 dBm, while the positive zero crossing point pulses is the probe light with an optical power of -10 dBm. Therefore, the stronger sinusoidal-modulated signal modulates the SOA gain, such that each of the positive zero crossing pulses experience different gain inside the SOA2, resulting in a peak power variation that corresponding to the temporal relative position between the peaks of the sinusoidal-modulated signal and the peaks of the zero crossing pulses. To explain it in more detail, if the peak of the pulse is aligned with or right behind the sinusoidal signal peak, then the pulse will experience gain depletion caused by the sinusoidal signal peak, resulting in a weak output pulse power. On the other hand, if the peak of the pulse appears before the sinusoidal signal peak, no gain depletion is experienced by the pulse, resulting in a strong output pulse power. That is to say, the pulse output power represents the phase difference between the reference signal and the VCO output. An optical bandpass filter (BPF2) is used to extract the output zero-crossing pulses, and a power level variation between minimum to maximum represents a phase difference variation between $-\pi/2$ to $\pi/2$, according to the phase error $e(\mathrm{t})$ relationship with the phase difference $\Delta\varphi(t)$ between the reference signal and VCO signals, i.e. $e(\mathrm{t}) = \sin^{-1}[\Delta\varphi(t)]$. A 10 GHz photodetector is used to convert the optical signal back to an electrical signal.

After the completion of phase detection, the detected phase difference is launched to the feedback controller, which is implemented by programming the microcontroller board with the necessary PID functions. An envelope detector is used to measure the root mean square (RMS) voltage of the output pulse train (Fig. 2(e)) from the phase detector. The microcontroller board takes the RMS value and perform the frequency correction calculation based on the proportional integral terms in standard PID control according to the equation $v(t) = k_P \cdot e(t) + k_I \cdot \int_0^t e(t)\,dt$, where $v(t)$ is the voltage output of the feedback controller, k_P and k_I denote the coefficients for the proportional and integral terms, respectively. Then the feedback controller outputs a corrected control voltage *v(t)* and apply to the VCO for minimizing the VCO's phase noise.

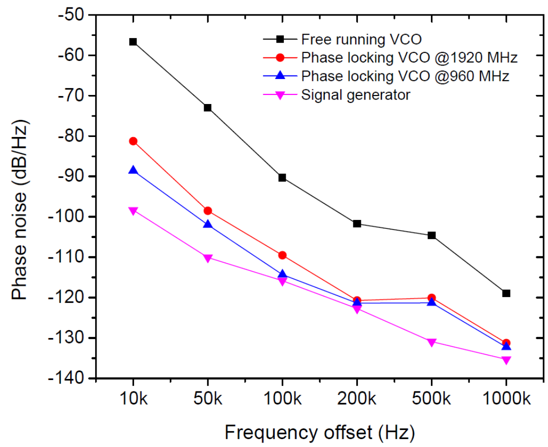

Fig. 3. Comparison of the phase noise performance between the free running and phase locking VCO.

In the experiment, a wideband VCO with operation frequency tunable from 867.1 MHz to 2631.9 MHz is used, while the signal generator is tunable from 9 kHz to 20 GHz. In the experiment, we characterize the PLL performance at two different VCO frequencies, 960 MHz and 1920 MHz. First, we measure the phase noise of the reference signal, which is shown by the pink inverted triangle data points in Fig. 3. Reference signal at 960 MHz and 1920 Hz show the same phase noise performance. Phase noise at frequency offsets of 10 kHz, 50 kHz, 100 kHz, 200 kHz, 500 kHz, and 1000 kHz are used as the comparison points due to the lack of direct phase noise measurement software. Single sideband phase noise of the free running VCO is measured as shown by the black square data points. When the optical microwave PLL is enabled, phase noise of the VCO at frequency of 960 MHz and 1920 MHz are measured, as shown by the blue triangle data points and red circle data points, respectively. According to the measured results in Fig. 3, the optical microwave phase lock loop has significantly suppressed the phase noise of the VCO by 25 dB and is approaching the limit of the reference signal generator.

3. Summary

We experimentally demonstrate an optical microwave phase lock loop with simple architecture based on the phase detection neural algorithm in the jamming avoidance response of Eigenmannia. The proposed PLL is capable of locking the phase of the high frequency sinusoidal signal generated from a VCO to a lower frequency reference signal generated from the signal generator. Using self-phase modulation for zero crossing point detection and cross gain modulation for phase comparison in two SOAs, the optical phase detector is implemented successfully based on the Eigenammia's JAR algorithm. The demonstrated design works well for a wide frequency range without the need of system modification; it is a simple and cost effective solution for frequency/phase synchronization between subsystems. Furthermore, the use of SOA enables potential integration on a chip for practical implementation.

Acknowledgement

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