A Fast-Locking Electro-Optic PLL (EOPLL) with Lock-in Calibration (LIC) and Harmonic Suppression for LiDAR

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Abstract *A novel EOPLL of FMCW LiDAR is proposed to eliminate the influence of temperature, process, and voltage (PVT) on the laser. Harmonic reduction mixer (HRM) with better rejection and LIC for improved EOPLL settling time are proposed.*

Introduction

Recently, with the popularity of autonomous driving, much effort has been devoted to the research and development of LiDAR (Light Detection and Ranging). Among different flavours of LiDARs, FMCW (Frequency Modulated Continuous Wave) LiDAR has received high attention due to its better anti-interference performance [1]. The laser in the FMCW LiDAR determines the performance of the LiDAR, and the nonlinearity of the laser directly leads to beat frequency shift and widening of the beat tone. However, the nonlinearity of the laser is very serious, and a small temperature change in the working environment will lead to a large nonlinearity. Even if there is often temperature feedback (TEC) inside the laser, it is far from enough. The laser is wavelength modulated, and the output frequency of the laser is $f = c/\lambda$ where c is the speed of light and λ is the wavelength. Therefore, the modulation frequency of the laser itself is nonlinear, as shown in Fig. 1. Therefore, an EOPLL must be introduced to precisely modulate the output frequency of the laser according to the input modulation waveform.

In an EOPLL system, the delay τ_{MZI} needs to be as small as possible to reduce the area for packaging. This results in a low beat frequency, with few beat cycles within a single repeat period, which places higher requirements on the settling time of the EOPLL. The long settling time of EOPLL cannot be used as the effective bandwidth (EBW) for detection, thus deteriorating the output bandwidth of the system and reducing the system accuracy. For example, for an autonomous driving FMCW LiDAR, when the output bandwidth (BW) of the laser is 4 GHz, the delay time is 1 ns, the repetition frequency (RPF) is 4 KHz, the beat frequency is 32 KHz, and the number of beat tone period is only 4, as shown in Fig. 1. It is very difficult for the EOPLL to settle within 4 CLK cycles because it needs to relock every time the direction of the drive triangle wave is switched. Therefore, the settling time of the EOPLL system is very important.

Previously, an EOPLL was built with discrete devices in [2] to verify its practicability, but its size and power consumption were prohibitive. [3] integrates the delay line and EOPLL using the charge pump structure EOPLL. Even if it uses lock calibration to reduce the EOPLL settling time after stabilization, the number of beat frequencies of the system cannot be too low. On this basis, [4] proposes an EOPLL with a mixer structure to reduce the settling time, but the locking frequency range of its system is narrow, requiring manual adjustment of the polyphase filter (PPF) and no locking calibration.

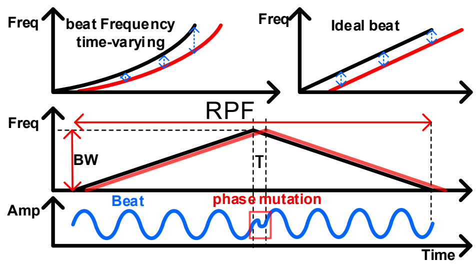

Fig. 1: The principle of FMCW LIDAR and the nonlinear principle of Laser.

Therefore, this paper combines the mixer structure EOPLL with the charge pump EOPLL, and proposed a novel EOPLL structure. It can achieve a wider loop bandwidth for faster locking and effectively filter out noise. The new PPF extends the lock frequency range of the EOPLL. A novel Harmonic reduction mixer (HRM) structure has also been introduced that suppresses the mixer's harmonics more efficiently than before. And a lock calibration is introduced to avoid the re-lock time caused each time the integrator switches. To meet the ability of multi-target recognition, the EOPLL can output a trapezoidal wave or triangular wave with variable slope through the improvement of the switch and integrator.

System Design

The EOPLL system consists of Transimpedance amplifier (TIA), single-ended-to-differential amplifier (SDA), polyphase filter (PPF), 4-to-8-phase converter (FEPC), HRM,

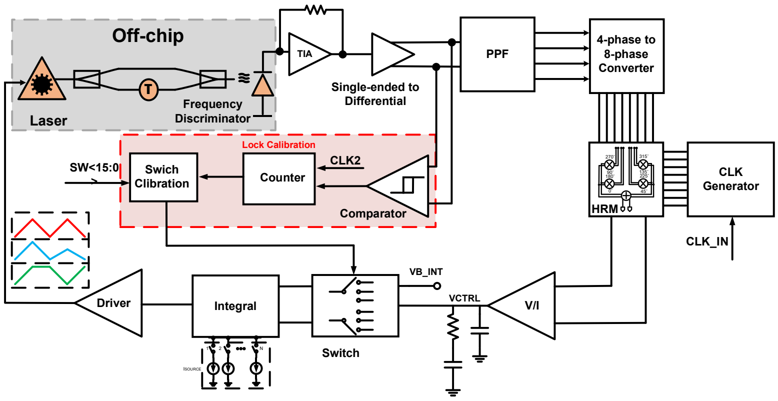

Fig. 2: Schematic of the proposed EOPLL.

CLK generator, voltage/Current (V/I) converter, switch, integrator, and driver. The triangular wave is generated by the integration of the input voltage of the integrator, and the laser is modulated by the laser driver. Mach-Zehnder Interferometer (MZI) generates a delay with a delay time of τ_{MZI}. The delay here is equivalent to the delay of the laser ranging from launching to the surface of the object and returning it. The beat frequency is produced by mixing delayed and undelayed optical signals. The beat frequency is detected by a photodiode (PD) and converted into a differential voltage by TIA and SDA. This signal passes through a three-stage PPF to generate signals of 0 degrees, 90 degrees, 180 degrees, and 270 degrees, and then the signal passes through an FEPC to become 0 degrees, 45 degrees, 90 degrees, 135 degrees, 180 degrees, 225 degrees, 270 degrees, 315 degrees signal. The eight-phase signals are then mixed with the eight-phase CLK respectively. The output of the mixer is connected to the switch module after V/I conversion and loop filter output. The switch generates a triangular wave by switching the electrodes of the two voltages. The switching of the switch and the switching of the integral current can output trapezoidal and variable-slope triangular waves respectively for multi-target recognition.

When the output of the mixer is directly used as the input of the integrator, such as [4]. At startup, since the output DC voltage of the mixer is the same, it is easy to cause the integrator to fail to integrate the triangular wave and enter a degenerate state. To avoid this situation, we added V/I converter and loop filter. The loop filter can not only adjust the loop bandwidth conveniently according to different lasers but also filter out the high-frequency harmonics of the mixer.

Harmonic Reduction Mixer

The principle of HRM is shown in Fig. 3. The three-stage PPF provides quadrature signals in the frequency range of 100-500 KHz. Using multi-stage cascading, its bandwidth can be wider than that of a single-stage PPF, which is suitable for more lasers and τ_{MZI}. Four phase vector addition units convert 4-phase signals into 8-phase signals through the vector sum of each pair. Four Hilbert cells mix the 8-phase beat signal with the 8-phase clock, effectively reducing the harmonics of the mixer output. The comparison between the proposed HRM and the HRM in [4] is shown in Fig. 4, the proposed HRM has a better suppression effect.

Lock-in Calibration

According to [3], the moment of switching will cause the phase discontinuity of the beat tone as shown in Fig. 1. To maximize the EBW, a

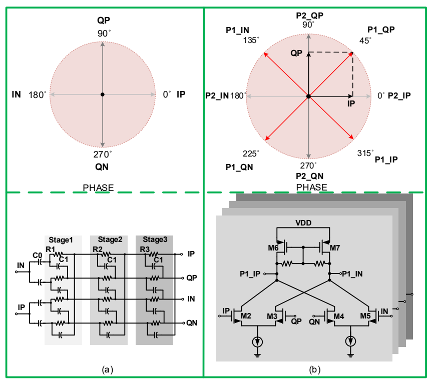

Fig. 3: (a) Schematic and phase of PPF, (b) Schematic of vector addition circuit and corresponding phase

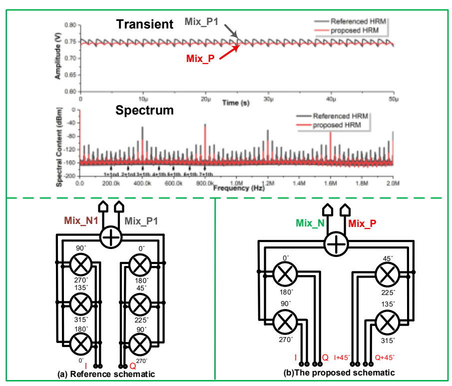

Fig. 4: Comparison of HRM in [4] and the proposed HRM.

Proportion Integral Differential (PID) algorithm is introduced to calibrate the switching time of the chirp. As shown in Fig. 2, the switch calibration module first converts the beat signal into a square wave through a comparator, and the counter calculates the duty cycle of the square wave. Then, the switching time of the triangular wave is adjusted by the switch calibration to minimize the phase discontinuity of the beat tone at the corners of the triangular wave modulation. SW<15:0> can set the RPF. This allows the EOPLL to lock in the shortest possible time, maximizing the EBW.

Experiment results

The EOPLL system uses a 1550 nm DFB laser with a 1 MHz linewidth. The chip uses a 65 nm CMOS process, and its photo is shown in Fig. 5. The power consumption of the chip is 68 mW (excluding the driver). The system uses 5 GHz laser bandwidth, 2 ns delay, 5 KHz RPF, 100 KHz beat frequency, and 8*100 KHz reference clock frequency.

For different configurations of the LiDAR system (including open-loop and various closed-loop configurations), the frequency domain results of the beat tone output by the TIA of the EOPLL are shown in Fig. 6. In open-loop, the frequency spectrum of the system beat tone is maintained for a while. It can be seen that the frequency of the beat tone is very unstable and changes over time, resulting in the frequency of the beat tone being a large bandwidth. The beat tone becomes very stable in the closed-loop, and the peak hold of the spectral remains unchanged. The spectrum of the beat tone is further cleaned

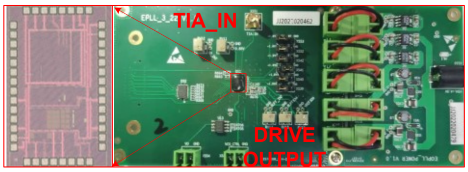

Fig. 5: Chip photos and test board.

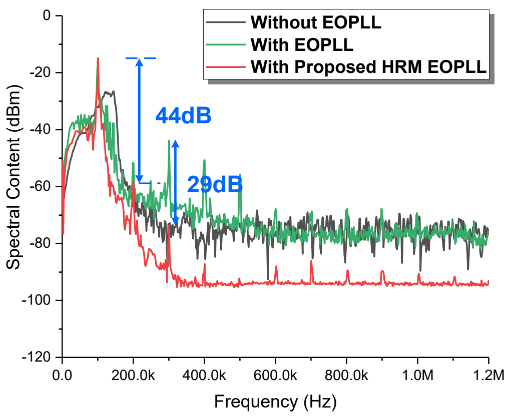

Fig. 6: Comparison of beat spectrum of open-loop, closed-loop and HRM.

up when plugging into the proposed HRM. It can be seen that the second harmonic is suppressed by more than 44 dB, and the third harmonic is suppressed by more than 29 dB.

In order to avoid relocking, we have introduced a LIC, which switches only at the peak of the sine wave of the beat note, which effectively shortens the relocking time of the EOPLL. As shown in Fig. 7, the results show that after introducing lock calibration, the lock time is reduced from 50% of the RPF period (5 beat frequency periods) to 10% (1 beat frequency period). The performance of the proposed system is summarized and compared to the prior art in Table 1. Compared with [2][4], it achieves excellent spurious rejection, effective bandwidth ratio, and better integration (BW*τ_{MZI}).

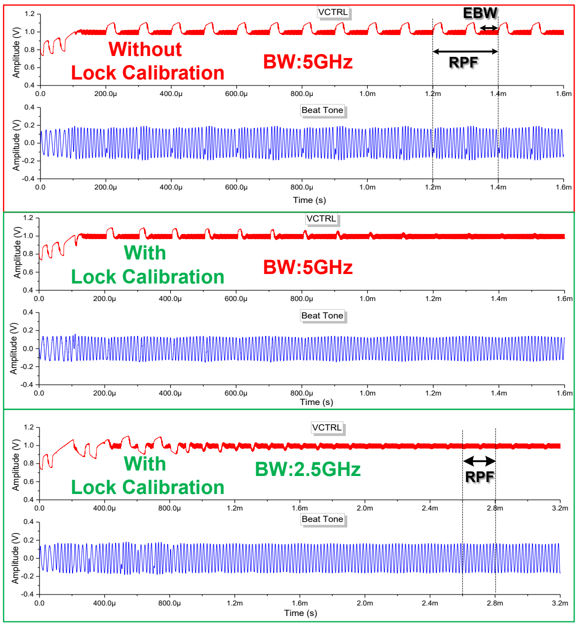

Fig. 7: Comparison before and after lock calibration.

Tab. 1: Comparison with state-of-art works.

	CLEO 2018[2]	RFIC 2019[4]	**This Work**
Technology,nm	Discret	65	**65**
Wavelenth,nm	1539	1546	**1550**
Chirp BW,GHz	16.67	16	**5**
BW*τ_{MZI}	2860	10	**5**
Spur Suppression	17dB	25dB	**29dB**
EBW / BW	N/A	N/A	**>90%**

Conclusion

In this paper, the new EOPLL enables the LiDAR to use a narrower FMCW bandwidth and a shorter delay line. The new HRM was verified to work well. The introduced LIC effectively solves the problem of wasting FMCW bandwidth during EOPLL locking.

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