Electro-optical phase-locked loop for hybrid integrated external cavity laser

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Abstract: We implement an analog EO-PLL for a III/V-Si_3N_4 hybrid integrated ECL to generate a highly-linear FMCW signal over multiple wavelengths. The ranging resolution is improved from 5 m to 35 cm for a 100-m target. © 2022 The Author(s)

1. Introduction

Frequency-modulated continuous wave (FMCW) lasers are indispensable devices for coherent light detection and ranging (LiDAR), suitable for solid-state optical phased array (OPA) systems [1, 2]. For an FMCW-based OPA-LiDAR system, the detection resolution is affected by the linearity of the frequency chirp, the detection range is determined by the dynamic coherence of the laser, and the elevation steering angle is dependent on the wavelength tuning range [3]. Recently, several integrated external cavity lasers (ECLs) incorporating Vernier filters have been demonstrated, which possess a wide wavelength tuning range and a narrow linewidth, quite suitable for the OPA-LiDAR applications [4]. Unfortunately, for most directly-modulated lasers, it is challenging to satisfy both wide wavelength tunability and high-frequency chirp linearity. Therefore, pre-distortion algorithms [5] and electro-optical phase-locked loop (EO-PLL) methods [6] have been implemented to linearize the frequency chirp. Previous works have been focused on improving the frequency chirp linearity of fixed-wavelength lasers such as distributed feedback (DFB) lasers [7]. The real-time linearization method suitable for the wavelength-tunable ECL has yet to be developed.

In this work, we propose an analog EO-PLL method combined with a pre-distortion algorithm to generate a FMCW signal using a III-V/Si_3N_4 hybrid integrated ECL. The FMCW signal has a large chirp bandwidth, high chirp linearity, and high dynamic coherence. High-accuracy distance detection at multiple laser wavelengths is hence realized.

2. Methods

Figure 1 (a) and (b) show the structure and microscope image of our ECL, respectively. It is composed of a reflective semiconductor optical amplifier (RSOA) and a Si_3N_4 external cavity. The Si_3N_4 external cavity consists of two cascaded add-drop micro-ring resonators (MRRs) and a thermo-optic phase shifter. These two MRRs work as a narrow Vernier filter with a large free spectral range (FSR) of 60 nm. It is used to select a single longitudinal laser cavity mode within a large wavelength tuning range [4]. When the resonances of these two MRRs are aligned with a longitudinal mode of the laser cavity, the net gain at the resonant wavelength reaches the maximum and the linewidth is the narrowest. The laser wavelength can be shifted from 1522 nm to 1578 nm by tuning these two MRRs. The maximum output power is 15.8 mW at the 1546 nm wavelength. We can use the phase shifter to change the laser cavity round-trip phase, thus modulating the laser frequency. Therefore, we can generate FMCW signals at any desired wavelength in the wavelength tuning range by adjusting the phase shifters and MRRs, which are required for OPA-LiDAR applications.

However, since the MRRs are fixed, phase shifter modulation alone causes detuning of the laser longitudinal mode from the center wavelength of the Vernier filter passband. This mismatch leads to degradation of the dynamic coherence and chirp linearity, which limits the detection range and resolution. Besides, the frequency chirp is not linear due to the thermal modulation, which can be corrected by various linearization methods. As mentioned above, the pre-distortion algorithm can improve the chirp linearity, but it is sensitive to environmental fluctuations and has poor accuracy for long-range detection. Therefore, we implement an analog EO-PLL combined with a pre-distortion algorithm to achieve a high-performance FMCW LiDAR system. A pre-distortion algorithm is applied first to ensure the EO-PLL works in the locking state. The EO-PLL offers real-time feedback for the system.

Figure 1(c) shows the EO-PLL implementation with a triangularly-chirped ECL. The MRR voltage controller provides the bias voltages to the two MRRs to set the laser to a desired working wavelength. The PID controller drives the phase shifter to generate a highly linear FMCW signal. The output of the laser is split into two parts. 90% output power is used for FMCW ranging experiments, and 10% is used for linearizing the frequency chirp. The 10% part enters a fiber-based Mach-Zehnder Interferometer (MZI) with a delay τ_{PLL} in one arm. This fiber-based asymmetric MZI and the balanced photodiode (BPD) act as a frequency discriminator, generating the beat signal with a frequency f_{beat}. Then, the beat signal is down-converted to generate the error signal by mixing it with an external reference electrical signal ($f_{ref} = f_{beat}$). Finally, the PID controller filters and amplifies the error signal, and then sums it with the pre-distortion driving signal generated by a waveform generator to compensate for the frequency drifts from a perfect linear sweep. The loop gain and the loop filter of the PID controller are optimized to lock the beat signal on the reference signal, generating a highly linear FMCW signal. In a locking state, the feedback ensures the phase of the beat signal is constant. Since the delay element in MZI is fixed, the chirp slope γ is robust to variations in laser nonlinearity, ambient temperature, and other environmental factors. In addition, the chirped ECL can be operated at arbitrary laser wavelengths by simply changing the voltages on the MRRs. This means that the optimized loop parameters at one wavelength are also suitable for locking the EO-PLL over the whole wavelength tuning range of the ECL.

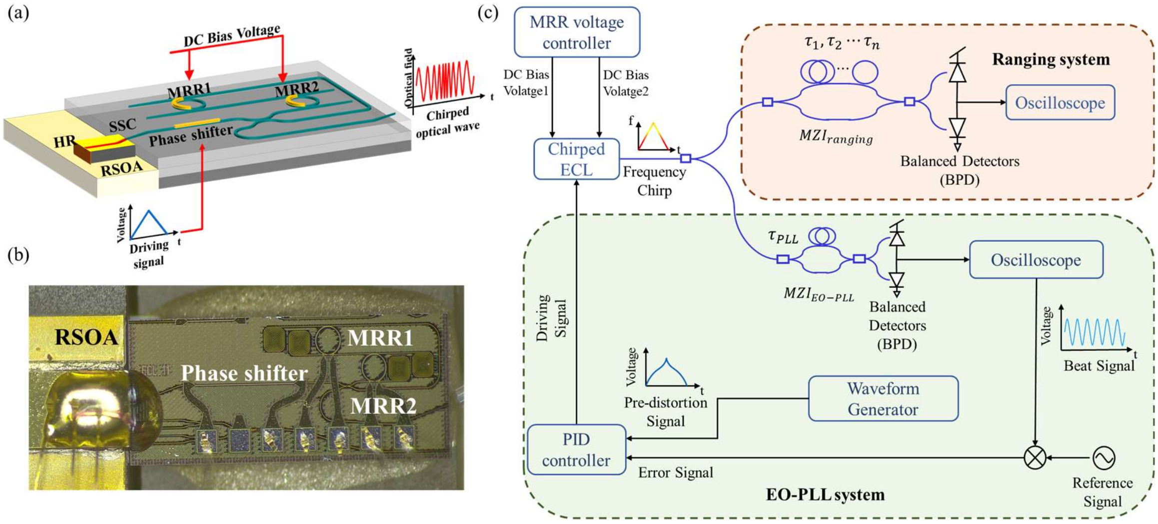

Figure 1. (a) Chirped optical wave generation in a wavelength tunable Si_3N_4 hybrid-integrated ECL. (b) Microscope image of the hybrid integrated laser. (c) Experimental setup for the ranging and EO-PLL systems.

3. Experiment results

We first optimized the driving signal using the pre-distortion algorithm proposed in our previous work at the wavelength of 1546 nm [4]. Figure 2(a) depicts the improvement of the chirp linearity under the pre-distortion algorithm. The chirp linearity increases to 99.82% (the corresponding $1 - R^2$ reduces to 3.8×10^{-6}) under the chirp bandwidth of 1.05 GHz and the chirp repetition rate of 1 kHz. The chirp bandwidth can be further increased by using the synchronous tuning method [4]. The pre-distortion driving signal is the same for the other laser wavelengths. In the EO-PLL, the τ_{PLL} is set to 73.3 ns, resulting in f_{beat} of 151 kHz. The EO-PLL system can provide real-time compensation to improve the chirp linearity and the laser dynamic linewidth. We used optical fibers of 100 m and 200 m long for ranging experiments with or without the EO-PLL. Figures 2 (b) and (c) depict the corresponding residual errors of the beat signal by applying the least-square linear fitting of the frequency chirp. With the EO-PLL, the root-mean-square (RMS) residual frequency error is lowered to 383kHz and 656kHz, which is around 1/5 of that without the EO-PLL, respectively.

Figures 2 (d)-(f) show the spectra of the received beat signal for the 100-m optical fiber with and without the EO-PLL at three different chirp center wavelengths. If only applying the pre-distortion algorithm without the EO-PLL, the beat signal broadening is very serious, increasing the ranging error. After adding the EO-PLL, the peak of the beat signal becomes sharper. At the wavelengths of 1539 nm, 1546 nm, and 1553nm, the full width at half maximum (FWHM) of the beat signal is 3.05 kHz, 2.24 kHz, and 3.56 kHz, corresponding to a ranging resolution of 30 cm, 22 cm, and 35 cm, which is very close to the theoretical value of 15 cm. In comparison, the FWHM of the beat signal is ~ 50 kHz without the EO-PLL, corresponding to the ranging resolution of ~ 5 m. From the spectra of the beat signal using EO-PLL, the frequency spurs are generated by the analog multiplier and can be further suppressed by introducing IQ single sideband (SSB) mixing and harmonic mixing (HR).

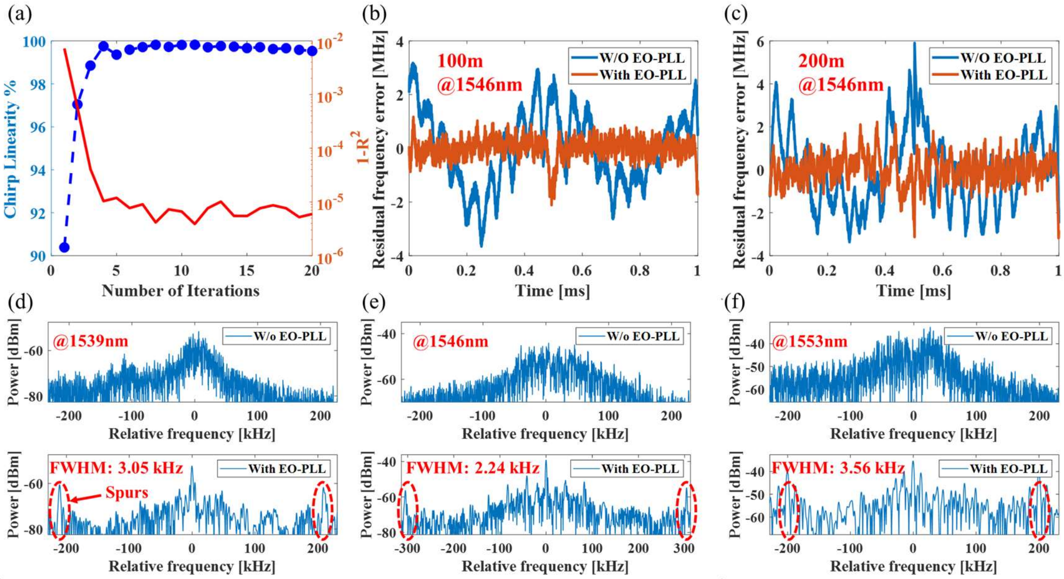

Figure. 2. (a) Chirp linearity improvement with iterations of driving signal. (b, c) Residual frequency error with and without the EO-PLL at the optical fiber length of (b) 100 m and (c) 200 m. (d-f) Fast Fourier transform (FFT) of the beat signal with and without the EO-PLL at the center wavelength of (d) 1539nm, (e) 1546nm and (f) 1553nm, respectively. The red dashed circles represent the frequency spurs. The fiber length is 100 m.

4. Conclusion

We have demonstrated an EO-PLL system that can effectively improve the chirp linearity of a hybrid integrated ECL over a wide wavelength tuning range. Within the 14 nm wavelength tuning range, we verified that the ranging resolution is improved from 5 m to 35 cm by using the EO-PLL for the 100-m target. The improved SNR and ranging resolution of the FMCW signal is highly applicable for FMCW-based OPA-LiDAR systems.

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5. References

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