High-precision FMCW ranging with a 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. A high range precision of 4.2 cm is achieved for a 200-m distance.**

Keywords*—*coherent LiDAR, external cavity laser, frequency modulated continuous wave laser, photonic integrated circuit.

I. Introduction

Frequency-modulated continuous wave (FMCW) lasers are essential devices for coherent light detection and ranging (LiDAR) [1, 2]. For FMCW-based ranging, the ranging resolution and precision are affected by the linearity of the frequency chirp, and the maximum detection range is ultimately determined by the coherent length of the laser. In an optical phased array (OPA) LiDAR system, the elevation angle is tuned by the laser wavelength. Therefore, the laser wavelength tuning range determines the steering range in the elevation direction. Recently, several integrated external cavity lasers (ECLs) incorporating Vernier filters have been demonstrated, which possess a wide wavelength tuning range and a narrow linewidth, well suitable for the OPA-LiDAR applications. Unfortunately, for most directly-modulated lasers, it is challenging to satisfy both wide wavelength tunability and high frequency chirp linearity. Therefore, pre-distortion algorithms [3, 4] and electro-optical phase-locked loop (EO-PLL) methods [5-7] have been implemented to linearize the frequency chirp. The state-of-the-art range precision is 5.8 μm at a 3 m distance [6], while it deteriorates rapidly with increasing distance. Previous works have been focused on improving the frequency chirp linearity at fixed wavelengths, such as distributed feedback (DFB) lasers [8]. The real-time chirp linearization method suitable for a wavelength-tunable ECL has yet to be developed.

In this work, we propose an analog EO-PLL method to generate a linear FMCW signal from a III-V/Si_3N_4 hybrid integrated ECL. The range resolution is improved by a factor of up to 58, compared to the free-running ECL. The high range precision of 4.2 cm is achieved at a distance of 200 m over a wavelength tuning range of 68 nm.

II. Methods

Fig. 1(a) and (b) show the structure and microscope image of our ECL, respectively. It consists of a reflective semiconductor optical amplifier (RSOA) and a Si_3N_4 external cavity. The Si_3N_4 external cavity incorporates two cascaded add-drop micro-ring resonators (MRRs), a thermo-optic (TO) phase shifter, and a tunable coupler. The MRRs with slightly different radii form a Vernier filter that can select the desired longitudinal lasing mode over a wide wavelength tuning range [4]. The TO phase shifter is used to change the laser wavelength. An FMCW signal is generated by modulating the phase shifter while the center wavelength is selected by tuning the MRRs. The tunable coupler, made of a Mach-Zehnder interferometer, can adjust the output power and the linewidth of the ECL. Benefiting from this design, we can ensure the ECL works in the optimal lasing condition over the whole wavelength tuning range. The frequency chirp is nonlinear due to the thermal modulation as well as the detuning of the longitudinal mode from the Vernier filter center. The chirp linearity can be improved by various pre-distortion methods. However, offline algorithms cannot adapt to real environmental changes and it has poor accuracy for long-range detection. Here, we implement an analog EO-PLL combined with a pre-distortion algorithm to achieve a high-performance FMCW ranging.

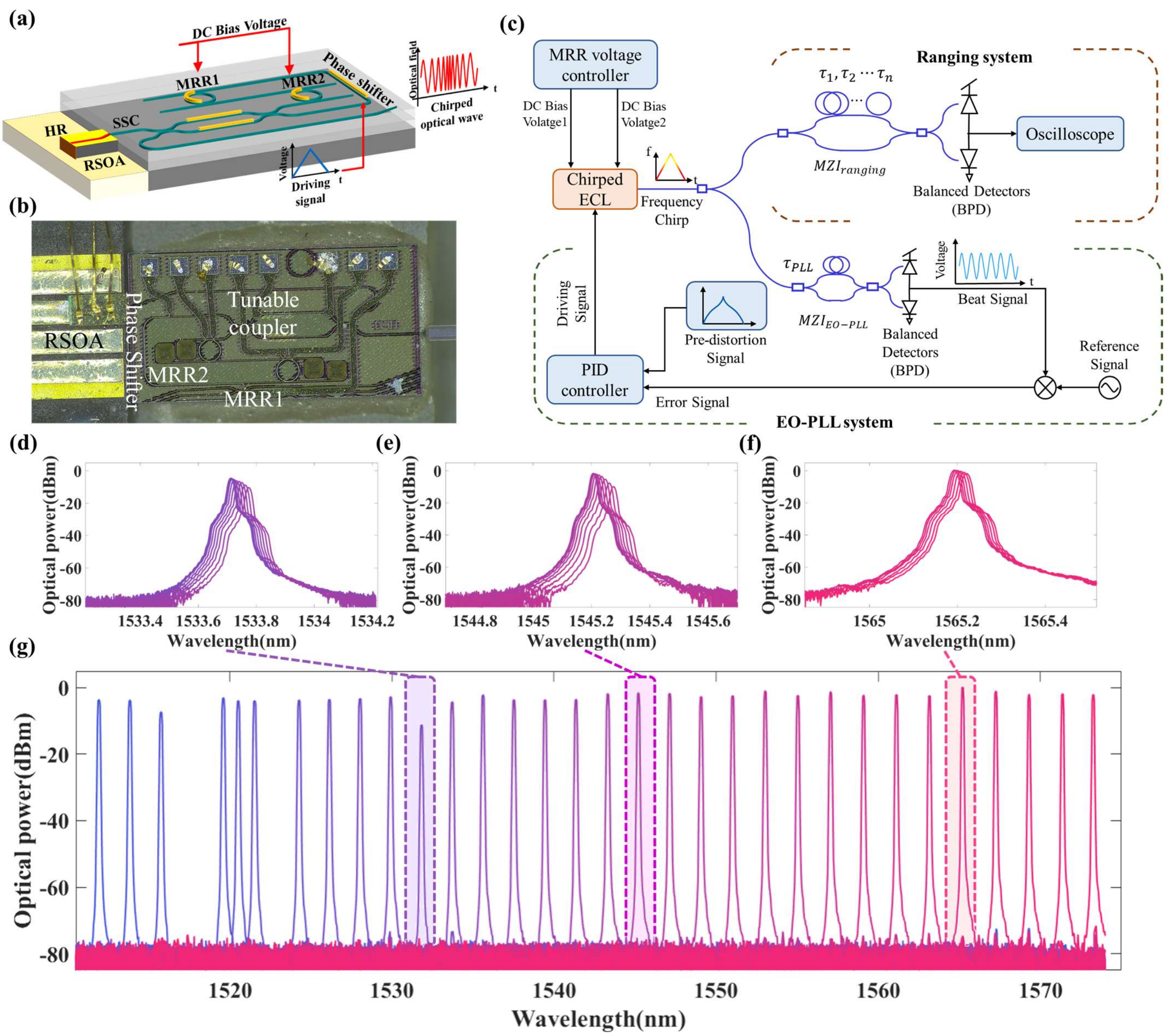

Figure 1. (a) Chirped optical wave generation in a wavelength tunable Si_3N_4 hybrid-integrated ECL. (b) Microscope image of the hybrid integrated laser. (c) Experimental setup for the ranging and EO-PLL systems. (d-f) Measured output spectra under

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continuous frequency sweep by driving the phase shifter. (g) Superimposed lasing spectra of the hybrid ECL by tuning the MRR Vernier filter.

Fig. 1(c) shows the EO-PLL with a triangular-chirped ECL. The MRR voltage controller applies the bias voltages to the Vernier MRRs to set the laser to a desired working wavelength. The PID controller drives the phase shifter to produce a highly linear FMCW signal. The laser output is split into two parts, with 90% of the output power being used for FMCW ranging and the other 10% for chirp linearization. The 10% part enters a fiber-based Mach-Zehnder Interferometer (MZI) with a delay τ_{PLL} in one arm. This fiber-based asymmetric MZI acts as a frequency discriminator, generating the beat signal with a frequency f_{beat}. Then, the beat signal is down-converted to produce 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, which is then added to the pre-distortion drive signal generated by the waveform generator to compensate for the frequency drift from a perfect linear sweep. As shown in Figs. 1(d) ~ (f), the laser wavelength is coarse-tuned by the Vernier filter and fine-tuned by the phase shifter. The tuning efficiency of the phase shifter is 0.039, 0.04, and 0.044 GHz/mW at the center wavelengths of 1533, 1545, and 1565 nm, respectively. Their slight difference results in wavelength-dependent chirp linearity and chirp bandwidth. The loop gain and the loop filter of the PID controller are optimized at each wavelength to lock the beat signal to the reference signal. Consequently, linearized FMCW signals can be generated over the entire wavelength tuning range (1512 nm to 1578 nm).

III. Experimental Results

We first optimized the driving signal using the pre-distortion algorithm proposed in our previous work at the wavelength of 1533, 1545, and 1565 nm respectively [4], generating an FMCW signal with a chirp bandwidth of 0.7 GHz and a chirp repetition rate of 1 kHz. The chirp bandwidth can be further increased by using the synchronous tuning method [3]. The EO-PLL system can provide real-time feedback to improve the chirp linearity and the dynamic linewidth of the ECL. Under the locking-on state, the ranging results are shown in Fig. 2(a) with the optical fibers being from 100 m to 230 m long. Fig. 2(b) depicts the corresponding range resolution by calculating the full-width half-maximum (FWHM) of the beat signal. The average range resolution improves from 1112, 1654, and 1800 cm under the free-running to 31.6, 38.6, and 30.7 cm in the locking-on state, respectively. The improvement is up to 58 times. Range precision is crucial for high-performance FMCW LiDAR systems. It can be measured by the standard deviation (σ) of the ranging results over a long time.

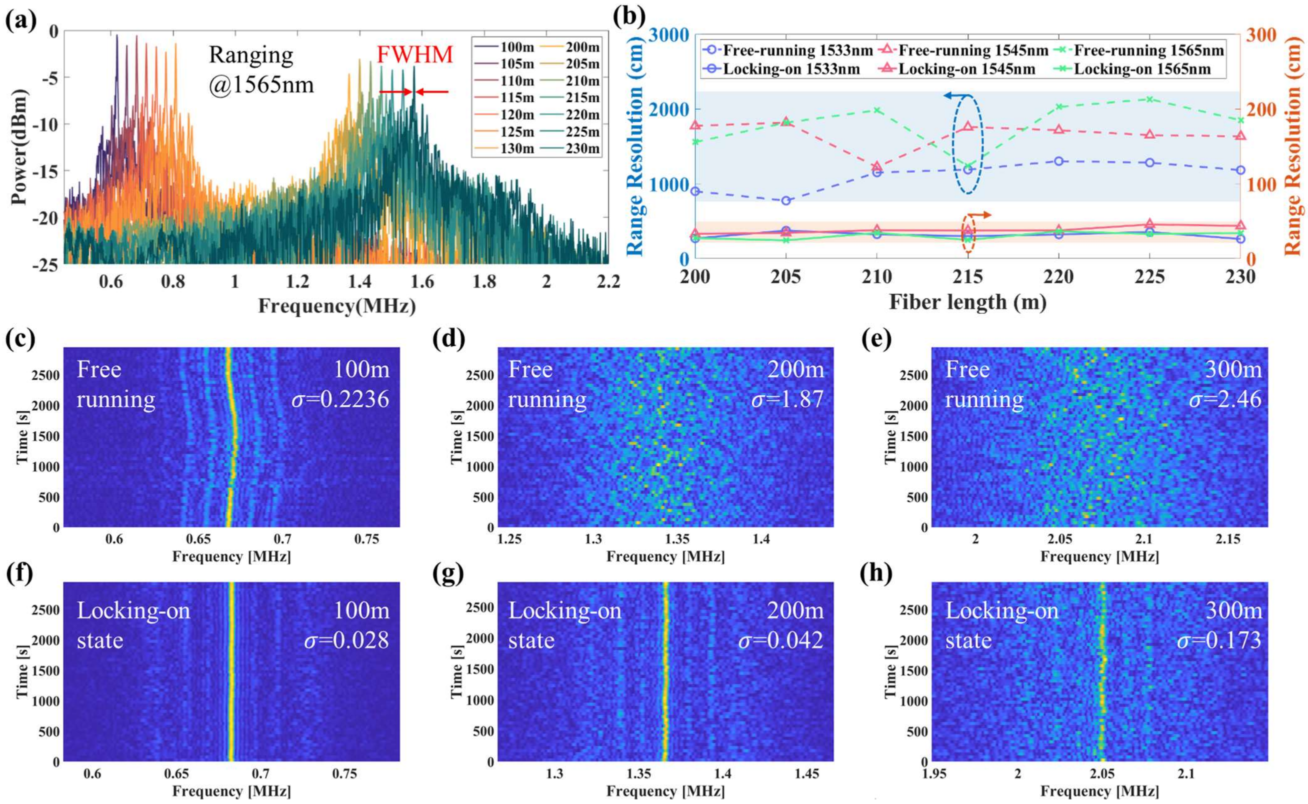

Figure 2. (a) Fast Fourier transform (FFT) of the beat signal under the locking-on state. (b) Comparison of the range resolution before and after locking-on. (c-h) Time-accumulated spectra of the beat signal for (c, f) 100-m, (d, g) 200-m, and (e, h) 300-m long optical fibers under the free-running and the locking-on state at the 1565 nm wavelength.

Figs. 2(c)-(h) shows the time-accumulated spectrum of the received beat signal for the 100-m, 200-m, and 300-m long optical fibers under the free-running and the locking-on state at 1565 nm. In the free-running state (where the pre-distortion algorithm is applied), the beat spectrum width and noise frequency components increase as the measurement distance becomes longer, thus deteriorating the range resolution and precision. The range precision deteriorates rapidly from 0.223 m to 2.46 m, leading to inaccurate ranging results. As shown in Figs. 2(f)-(h), with the EO-PLL applied, the beat signal is stable and the spectrum has less noise. The range precision is improved to 0.028, 0.042, and 0.173 m, respectively, up to 445 times higher compared to the free-running case. The analog multiplier generates some undesired frequency spurs, which can be further suppressed by introducing IQ single sideband (SSB) mixing and harmonic mixing (HR) [7].

IV. CONCLUSION

We have demonstrated an EO-PLL system that effectively improves the chirp linearity of a hybrid integrated ECL over a wide wavelength tuning range. The range resolution and precision are improved by a factor of 58 and 445 by using the EO-PLL for a 200-m target, respectively. The improvement is critical for the FMCW-based LiDAR system.

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