Monolithic FMCW Tunable Laser with High Modulation Linearity and Narrow Linewidth

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Abstract *We demonstrate a monolithic FMCW laser based on InP generic platform. The laser shows 51-nm tuning range with the linewidth down to 16 kHz. By electronically modulating an intra-cavity phase section, a frequency modulation signal with 99.99% linearity and 1.8-GHz chirp range is directly achieved.*

Introduction

With the emerging of intelligence automation, LiDAR (Light Detection and Ranging) becomes increasingly essential as high-precision 3D imaging system and remote sensor. For applications such as autonomous driving and robotics, they require LiDAR to measure complex surrounding environments and situations. Owing to the higher receiver sensitivity and velocity detection capability, frequency modulated continuous wave (FMCW) LiDAR is proposed for better performance and extended application areas [1].

FMCW LiDAR is based on a linear modulation of the optical carrier frequency, where its frequency sweep linearity directly affects the detection resolution and accuracy. The common method to generate a frequency modulated signal is through direct current modulation of a DFB laser [2] or use an external single side band modulator [3]. Due to the intrinsic nonlinear relation of the output frequency with respect to injection current, direct gain current modulation method usually needs an additional frequency tracker [4] or linearization by means of a pre-distortion algorithm [2]. Both of them increase the system complexity and cause additional data acquisition delay. For the external modulation method, it induces additional optical loss and requires complex driving and controlling circuits. Recently, hybrid integrated external cavity laser based FMCW source has been demonstrated by tuning the intracavity thermal phase shifter [5]. However, thermal tuning is relatively low speed and high power consumption.

The long-distance ranging resolution of FMCW LiDAR is limited by the laser linewidth [6]. To enable ranging of a few hundred meters, a narrow-linewidth laser is required. Wavelength tuning of the laser source is also very valuable in several LiDAR architectures, for example, to carry out spectral LiDAR or to realize beam steering in combination with dispersive gratings. A two dimensional beam steering could be realized through a tunable laser and an one dimensional optical phase array (OPA), which would greatly reduce the complexity [7]. A wider wavelength tuning range corresponds to a larger scanning angle.

In this paper, we experimentally demonstrate a monolithically integrated widely tunable FMCW laser source based on InP generic photonic integration platform from SMART Photonics, where we employ an intra-cavity phase modulator to realize a highly linearity frequency sweeping and large frequency chirp range. The proposed laser structure has realized a wide wavelength tuning range with a narrow linewidth.

Laser Structure and Experimental Setup

Fig. 1 (a) depicts a microscope picture of the proposed laser. The corresponding schematic view of the cavity structure is shown in Fig. 1 (b). The fabrication of the chip was carried out by SMART Photonics. It has a ring cavity and an unbalanced 2X2 MMI with 85:15 coupling ratio to partially feedback the optical field to the cavity (85%) and partially (15%) output. It is designed to balance the mirror loss and output power. An MMI reflection mirror is implemented on the right bottom port of the 2X2 MMI to suppress the clockwise (CW) mode and only counter clockwise (CCW) mode would oscillate. Inside the laser cavity, three cascaded AMZIs with carefully designed free spectrum ranges (FSRs) are implemented to realize efficient mode filtering and wide tuning range. The achieved tuning range would also be affected by the bandwidth of the gain spectrum. The FSRs of these three filters are 65 GHz, 850 GHz and 9.1 THz, respectively. The total physical circumference of the ring laser cavity is 16.4 mm and contains an 1000-um-long gain section. Thanks to the cavity loss control, the long cavity length, and the small active-passive length ratio, we would expect a narrow linewidth operation of this laser. A 1.88-mm-long intra-

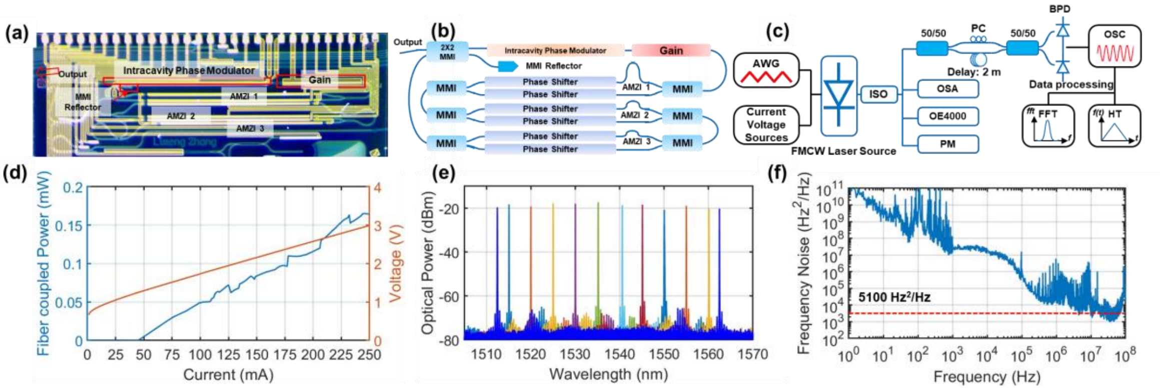

Fig. 1: (a) Microscope picture of the monolithic tunable FMCW laser chip. (b) A schematic view of laser cavity structure. (AMZ: asymmetric Mach-Zehnder interferometers) (c) The setups for the demonstrated the FMCW laser source. (AWG: Arbitrary Waveform Generator; ISO: in-line optical isolator; OSA: optical spectrum analyzer; PM: optical power monitor; PC: polarization controller; BPD: balanced photon detector; OSC: oscilloscope; FFT: fast Fourier transform; HT: Hilbert transform) (d) Typical fiber-coupled LIV curve the laser. (e) Optical spectra under different operation wavelengths. (f) Laser frequency noise spectrum at 1535 nm.

cavity phase modulator was employed along with the gain section to realize lasing frequency modulation. Through carefully design of epitaxial stack, doping profile and optical field distribution of the phase modulator, a high linearity phase voltage relation is achieved experimentally. To describe the relationship between the phase tuning of intracavity phase modulator and output frequency modulation, we start with a general equation for a laser with active and passive sections in Eq. (1) [8].

$$\lambda = \frac{2}{m}(n_a L_a + n_p L_p) \qquad (1)$$

Where m is the longitudinal mode number and λ is the lasing wavelength. n_a (n_p) and L_a (L_p) are the refractive index and length of the active (passive) section. Through equation transformation and differentiation of Eq. (1), we can get Eq. (2).

$$\frac{2\pi n_a L_a}{c}\Delta f = \Delta\left(\frac{2\pi n_p L_p}{\lambda}\right) = \Delta\Phi \qquad (2)$$

Where f is the lasing frequency and c is the speed of light. As can be seen, if there is a linear phase modulation ($\Delta\Phi$) of the passive section, we can get a linear lasing frequency modulation (Δf).

Fig. 1 (c) shows the setup to investigate the performance of the laser source in FMCW ranging. The integrated laser was mounted on a PCB interposer and electrically contacted through wire bonding. The whole interposer was fixed on a temperature-controlled stage with an operation temperature of 18 °C. An 100-kHz triangle signal was applied on the phase modulator through an arbitrary waveform generator (AWG SDG6052). An even higher frequency modulation can be expected for the electro-optical phase modulator in the further experiments. The modulated optical signal is sent to a fibre based unbalanced Mach–Zehnder interferometer (MZI) after an inline optical isolator. The relative delay length of the two arm is 2 meter. The beating signal is captured by a real-time oscilloscope (OSC) after a balanced photodetector.

Experimental Results

Fig. 1 (d) shows a typical measured power-current-voltage (LIV) curve. In the measurement, the AMZI filters and the phase modulator are biased to realize a single mode operation and then fixed in the gain current sweep. The differential resistance is 8.5 Ohm and the threshold current is 42 mA. Power versus current curve also shows a mode jump free current range from the threshold to 100 mA. The output power was measured after coupling into a standard single mode fibre, where a fibre coupled power of 0.175 mW is achieved which contains ~9.5 dB insertion loss. By electrically tuning the bias voltage of the phase sections of each AMZIs, wavelength tuning from 1512 nm to 1563 nm is achieved as the optical spectra shown in Fig. 1 (e). In the whole tuning range, the side mode suppression ratio (SMSR) is larger than 40 dB. The frequency noise of the laser was measured using an OEwaves OE4000 laser noise analyzer. A measured frequency noise spectrum at 1550 nm is shown in Fig. 1 (f). The obtained white-noise-limited frequency noise level is 5,100 Hz^2/Hz, giving a Lorentzian linewidth of 16 kHz.

The orange line in Fig. 2 (a) shows the output triangle waveform of the AWG, where the voltage sweep range is from -2.5 V to -5 V with a 100-kHz modulation frequency. By applying this signal to the phase modulator, the measured real time waveform in the OSC at 1531 nm is shown as the

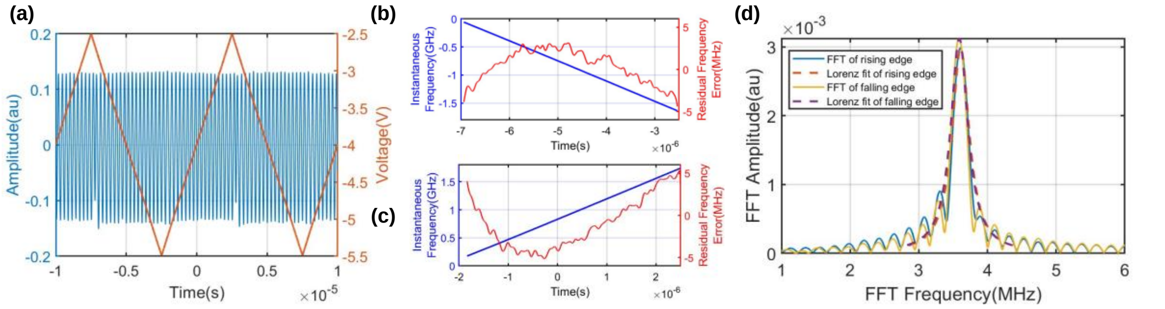

Fig. 2: (a) The measured real time waveform in the OSC (blue line) and the output triangle waveform of AWG (orange line) at 1531 nm. The extracted instantaneous frequency (blue line) and the residual frequency error (red line) of rising edge (b) and falling edge (c). (d) Fourier transform spectra of the beating frequency at the rising and falling edges with their Lorenz fitting.

blue line in Fig. 2 (a). We investigate the linearity of this signal through both Hilbert transform and Fourier transform. Fig. 2 (b) and (c) show the instantaneous frequency versus time of both rising and falling edges extracted from the real time waveform through Hilbert transform. As can be seen, a chirp range of 1.8 GHz is achieved. The calculated linearity correlation coefficient is as high as 99.99% for both edges. The RMS residual frequency errors are 2.47 MHz and 4.49 MHz for the rising and falling edges, respectively.

Fig. 2 (d) shows the Fourier transform spectrum of the beating signal and its Lorentz fitting curve. By using the -3 dB bandwidth of the FFT spectrum (Δ_{FFT}), a spatial detection resolution of 17 cm is calculated under Eq. (3).

$$\mathrm{d}L = \frac{c}{n}\frac{\Delta_{FFT}}{\beta} \qquad (3)$$

Where c is the speed of light, n is the refractive index of fibre and β is the slope of modulation waveform (in MHz/μs).

We then investigated the FMCW ranging performance of the laser under different working wavelengths. Among a wavelength range of 1512-1563 nm, we achieved an RMS residual frequency error lower than 7.9 MHz and a linearity better than 99.97%.

Conclusions

We experimentally demonstrated a monolithic integrated FMCW laser source with a frequency modulation linearity as high as 99.99% in a chirp range of 1.8 GHz, a Lorentz linewidth down to 16 kHz and a wavelength tuning range up to 51 nm. Frequency modulation of this laser is directly achieved through a voltage driving signal applied to the intracavity phase modulator. Under different working wavelengths, the extracted RMS residual frequency error is below 7.9 MHz and the linearity better than 99.97%. The simplicity of the frequency modulation control and its high linearity make it a promising laser source for FMCW LiDAR systems.

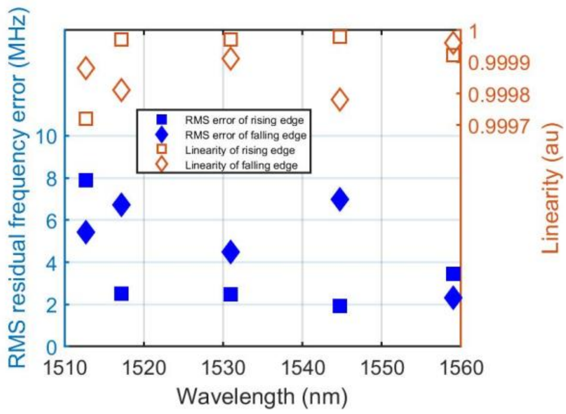

Fig. 3: RMS residual frequency error (filled blue square and diamond) and linearity (orange square and diamond) of both rising and falling edges as a function of wavelength.

Acknowledgements

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References

[1] D. Bastos, P. P. Monteiro, A. S. R. Oliveira and M. V. Drummond, "An Overview of LiDAR Requirements and Techniques for Autonomous Driving," 2021 Telecoms Conference (ConfTELE), Leiria, Portugal, 2021, pp. 1-6, DOI: 10.1109/ConfTELE50222.2021.9435580.

[2] X. Zhang, J. Pouls, M. C. Wu, "Laser frequency sweep linearization by iterative learning pre-distortion for FMCW LiDAR", Optics Express, Vol. 27, No. 7, pp. 9965–9974, DOI: 10.1364/OE.27.009965

[3] M. Kamata, Y. Hinakura and T. Baba, "Carrier-Suppressed Single Sideband Signal for FMCW LiDAR Using a Si Photonic-Crystal Optical Modulators," in Journal of Lightwave Technology, vol. 38, no. 8, pp. 2315-2321, 15 April15, 2020, DOI: 10.1109/JLT.2020.2965571.

[4] H. Jang, J. W. Kim, G. H. Kim, C. H. Park, S. W. Jun, M. Jo, H. Lee, C.-S. Kim, "Simultaneous distance and vibration mapping of FMCW-LiDAR with akinetic external cavity diode laser", Optics and Lasers in Engineering, Vol 160, 2023, 107283, DOI: 10.1016/j.optlaseng.2022.107283.

[5] C. Liu, Y. Guo, R. Xu, L. Lu, J. Chen, and L. Zhou, "Electro-optical phase-locked loop for hybrid integrated external cavity laser," in Optical Fiber Communication Conference (OFC) 2023, paper M3F.7. DOI: [OFC-2023-M3F.7]

[6] W. Yi, Z. Zhou, Z. Liu, P. Bayvel, and R. I. Killey, "Impact of Laser Phase Noise on Ranging Precision Within and Beyond Laser Coherence Length in FMCW LiDAR," in Optical Fiber Communication Conference (OFC) 2023, paper M3F.3. DOI: [OFC-2023-M3F.3]

[7] H. Hashemi, "A Review of Silicon Photonics LiDAR," 2022 IEEE Custom Integrated Circuits Conference (CICC), Newport Beach, CA, USA, 2022, pp. 1-8, DOI: 10.1109/CICC53496.2022.9772845.

[8] L. A. Coldren, S. W. Corzine, M. L. Mašanović, " Diode Lasers and Photonic Integrated Circuits," John Wiley & Sons, 2012, pp. 58. DOI: 10.1002/9781118148167.ch2