Feasibility study of integrated tunable laser with intra-cavity linear phase modulator for FMCW LiDAR

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A tunable laser source operating in the C-Band for frequency modulated continuous wave operation is studied. The laser cavity is based on cascaded Mach-Zehnder interferometers for wavelength filtering and a highly linear intra-cavity phase modulator. The integrated laser is based on InP generic photonic integration, and the complete laser structure was studied by means of circuit simulations using building block models that incorporate experimental data. A frequency chirp range of 8GHz with a linearity correlation coefficient as high as 99.98% is obtained. By using the generated signal, a detection range resolution of 1m is achieved at a 30-meter distance, whereas a 18cm resolution is expected for an ideal linear intra-cavity phase modulator.

1. Introduction

In recent years, LiDAR has received large attention due to the new emerging applications in autonomous vehicles and augmented reality (AR). Among many proposed LiDAR technologies, frequency modulated continuous wave (FMCW) utilizes a frequency swept laser source and coherent detection, which dramatically relaxes the optical power requirement and can achieve high resolution distance and velocity measurement simultaneously.

In FMCW LiDAR, the detection distance is converted to a beat note of received instantaneous frequencies between target and local reference [1]. Under this coherent detection framework, the nonlinearity of the laser frequency sweeping will degrade detection accuracy and reduce the signal-to-noise ratio. To achieve better performance, large effort have been dedicated to achieve a linear frequency sweep [2-4]. One approach is using a frequency tracker, which feeds back the error signal and correct the laser output in real-time [2]. It achieves very good results, however, the frequency tracker requires fast electronics, increases the complexity and cost, and is not easy to integrate with the laser source. Another approach is using pre-distortion of the laser source [3]. It has been successfully used in different kinds of lasers like DFB and VCSEL and does not need a complicated control loop. However each laser needs unique training and lasing parameter change through aging is also need to be considered. Single sideband modulation has also been proposed to realize linear frequency tuning, however it needs complex driving signals at GHz speeds and the frequency range is limited by the bandwidth of the external modulator [4].

Generation of a linear frequency sweep directly using monolithic tunable lasers would be very attractive. To date, monolithic tunable lasers have not been able to generate linear frequency sweep due to their intrinsic nonlinear frequency tuning through, e.g. current injection [5]. In this paper, we employ a highly linear intra-cavity phase modulator instead of current-injection phase-tuning-section to realize the frequency sweep. The complete laser structure was studied by means of circuit simulations using building block models that incorporate experimental data. We simulate the optical spectra under intra-cavity phase modulator voltage sweeping and calculate the residual nonlinearity ($1-R^2$) and root mean square (rms) error of frequency modulation. Finally, we use the generated frequency modulation to calculate the detection range resolution in a LiDAR system. As a comparison, the performance of an ideal linear phase modulator is also simulated.

2. Laser structure and circuit simulation model

The schematic view of the proposed widely tunable laser is shown in Fig 1. It contains three cascaded asymmetric Mach-Zehnder interferometers (AMZIs) to realize efficient mode filtering and wide tuning range. Each AMZI is composed of two MMIs and two phase modulators (PM) in both arms. The detailed performance of the AMZIs based laser can be found in our previous published paper [6]. In this paper, we add an additional intra-cavity phase modulator along with the gain section to realize lasing frequency modulation. The phase modulator based on an InP generic photonic integration platform has almost linear dependence of sweeping the driving voltage.

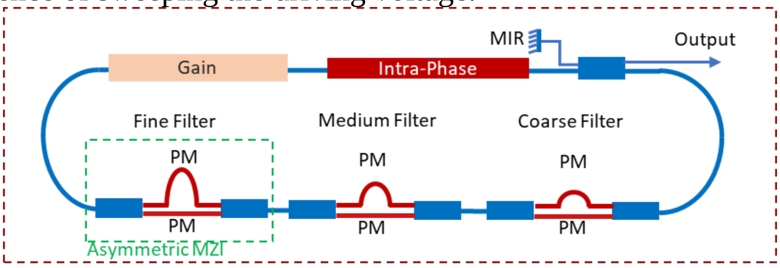


Fig 1. Schematic of laser structure consist of three cascaded asymmetric Mach-Zehnder filters, an intra-Phase, Gain section, and a multimode interference reflector (MIR).

The circuit model of the proposed laser structure is then built in a commercial software, Lumerical Interconnect [7], where the related building block models, that contain waveguides/MMIs/multimode interference reflector (MIR), incorporate experimental data from SMART Photonics. We also take measurements on the phase modulator from SMART Photonics. The measurement phase versus voltage results of a 2.5-mm phase modulator and the implemented simulated curve from the circuit model are also shown in Fig 2. As can be seen, the $V_{\pi}L$ of this PM is 8 V·mm and the linearity correlation coefficient is 99.93% in the simulated curve from 0V-10V. This is realized by a fine material structure design to control the weights of different field effects in the phase modulator, including the Pockels effect, Kerr effect, Plasma effect, Band filling effect [8]. As the loaded voltage continues increasing, the phase shift becomes larger and starts quadratically increasing due to the quadratic field effects, like Kerr effect, which start to dominate at high voltages.

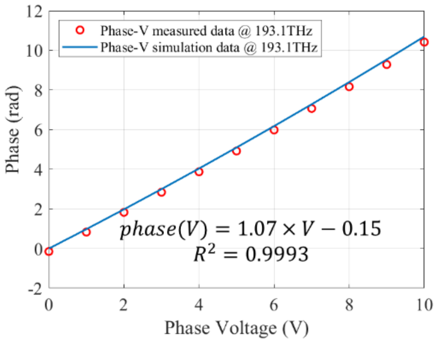


Fig 2.Phase response to reverse bias voltage.

3. Impact of phase linearity

By tuning the driving voltage in the phase modulator, the output lasing frequency can be continuously swept. The simulated optical spectrum is shown in Fig.3(a). A continuous frequency chirp range of 8 GHz can be achieved under the optimization of the Free spectrum range (FSR). A side mode suppression ratio larger than 30 dB is achieved within the whole chirp range.

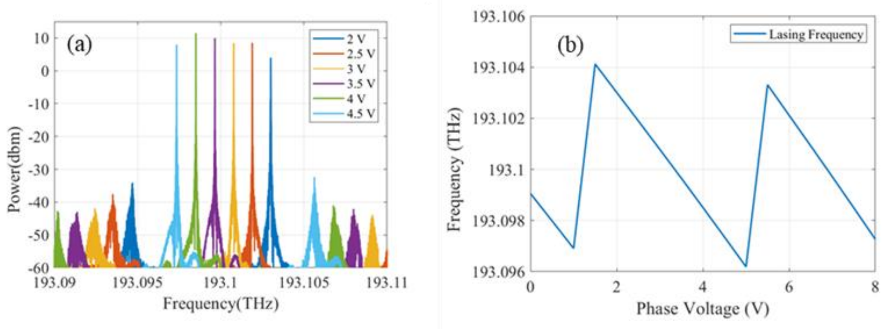
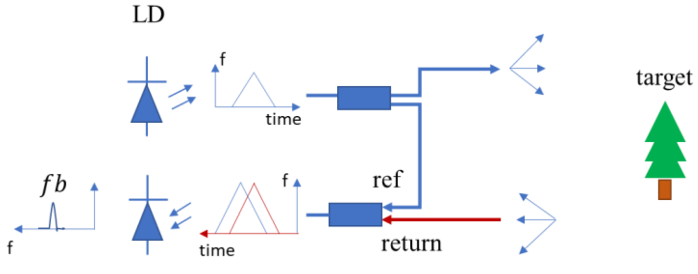


Fig 3.(a)Simulated optical spectrum and (b)lasing frequency versus voltage of phase modulator.

The lasing frequency versus the voltage of the phase modulator is shown in Fig 3(b). By using a linear fit, the residual nonlinearity of frequency sweep is about 2×10^{-4} for a voltage range 1.5-5 V, and the rms error is 20MHz. By employing this FMCW optical source in a LiDAR system shown in Fig 4(a), the achieved detection range resolution can be derived from the FWHM of the beating signal. The reference and returned signal with 20MHz rms error are plotted in Fig 4(b), which are mixed in a photodiode. After FFT calculation, the resolution 1 m for a target 30 meters away is derived from the beating signal in Fig 4(c). In the simulation, the frequency sweeping speed is set as 800 MHz/μs and the period of triangle waveform is set as 10 μs.

For estimating the impact of phase modulator linearity on the LiDAR system, we also employed an ideal linear phase modulator and simulated the detection range resolution. With an ideal phase modulator implemented in the laser circuit, a 3MHz rms error is achieved. As shown in Fig 4(d), the reference and returned signal with 3MHz rms error are plotted and the range resolution 18cm is derived from Fig 4(e) at the same conditions.



(a)

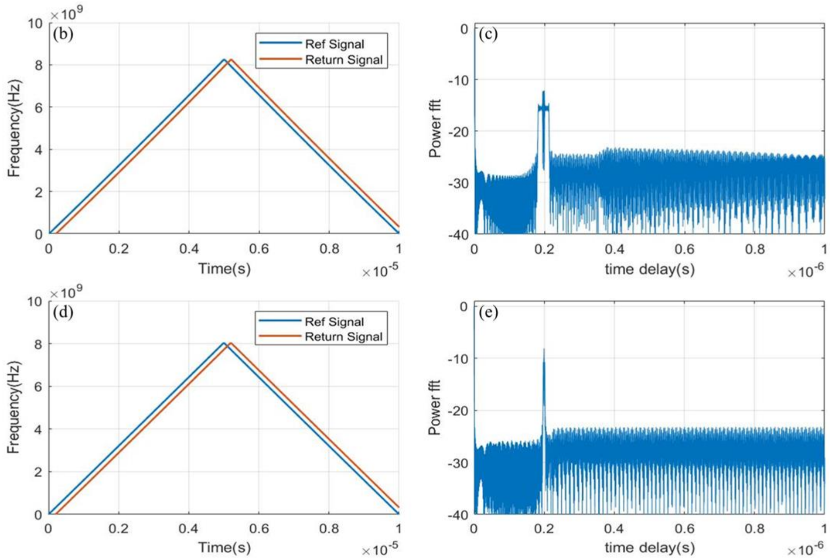


Fig 4 .(a) Schematic of an FMCW LiDAR. (b)(d)The chirp of optical frequency versus time for the reference signal and returned signal corresponding to rms 20MHz and 3MHz, respectively.(c)(e)Beating signal corresponding to rms 20MHz and 3MHz, respectively.

4. Conclusion

In this paper, a promising FMCW laser concept for LiDAR systems is introduced by driving a highly linear intra-cavity phase modulator. The complete laser structure was studied by means of circuit simulations using building block models that incorporate experimental data. We simulate the optical spectra under intra-cavity phase modulator voltage and calculate the residual nonlinearity($1-R^2$) and root mean square (rms) error of frequency modulation. A detection range resolution of 1m for a target of 30m is achieved based on the generated frequency modulation signal. As a comparison, a detection range resolution of 18cm is expected for a purely linear phase modulator.

Acknowledgments

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