Frequency Modulated Continuous Wave Narrow Linewidth Laser Diode Based on Self-injection locking with External Micro-ring Resonator

Liwei Tang[1,2], Shuai Shao[1,2], Sigang Yang[1,2], Hongwei Chen[1,2], Minghua Chen[1,2]
[1] Department of Electronic Engineering, Tsinghua University, Beijing, 100084, China
[2] Beijng National Research Center for Information Science and Technology (BNRist), Beijing, 100084, China
e-mail: chenmh@tsinghua.edu.cn

ABSTRACT

A chip-scale frequency modulated continuous wave (FMCW) laser is implemented by coupling the distributed feedback (DFB) laser to an external high-Q micro-ring resonator based on Si_3N_4 waveguide. By self-injection locked, the laser realizes continuous tuning and frequency modulated without mode hopping. The lasering frequency is tracing the resonant frequency of the micro-ring which is tuned by thermo-optic (TO) effect. The laser shows a DC frequency tuning range of 9.1 GHz with a low noise of 3.7 kHz linewidth. Dynamic time-frequency domain analysis of the frequency modulation is also demonstrated, which has a potential application for light detection and ranging (LIDAR).

Keywords: Integrated optics, semiconductor laser, frequency sweep

1. INTRODUCTION

Coherent optical communication, optical coherence tomography (OCT), LIDAR, etc., have a rapidly rising demand for the FMCW laser source. Wideband tunable FP laser has been proposed by introducing the Vernier effect, while its mode hopping limits the modulation accuracy and bandwidth [1]. In this paper, a DFB laser packaged with micro-ring resonator based on Si_3N_4 waveguide is demonstrated, showing a continuous frequency modulation with narrow linewidth. The micro-ring resonator fabricated with low-loss Si_3N_4 waveguide featuring a Q (quality factor) value of 2×10^5, realizing a linewidth of 3.7 kHz. Resonant wavelength is tuned by the voltage applied to the electrode which is used to heating the waveguide. Based on the TO effect, the static tuning range is up to 9.1 GHz around 1547.1 nm and the modulation bandwidth is 0.9 GHz in 1 ms enabling the LIDAR based on FMCW.

2. PRINCIPLE and EXPERIMENT

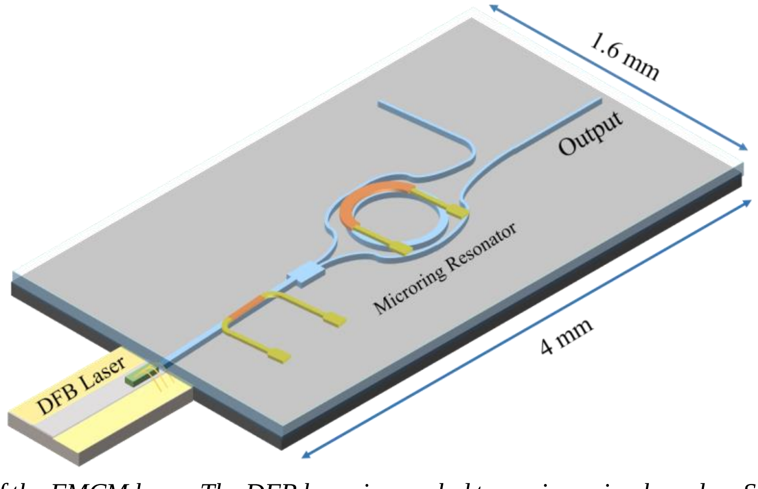

Figure 1. Diagram of the FMCM laser. The DFB laser is coupled to a micro-ring based on Si_3N_4 waveguide where the blue line represent the waveguide, the red and yellow line represent the heating resistor and electrode.

The optical source consists of commercial DFB laser diode (LD) and the extern micro-ring resonator which is shown in Fig. 1. In static operation, the micro-ring resonator can be regarded as a filter and mirror which reflects the selective wavelength and injects it into the DFB laser while outputting the filtered light. The efficiency of self-injection decided by the ration of Q of the laser and external cavity. The suppression of the linewidth is described by equation 1 derived for the reduction of close-in phase noise of the laser [2].

$$\eta = \frac{\Delta\nu_0}{\Delta\nu} = 1 + \sqrt{\frac{P_r}{P}(1+\alpha^2)}\frac{Q}{Q_{LD}} \quad (1)$$

where $\Delta\nu_0$, $\Delta\nu$ represent the linewidth after and before the injection respectively, Q, Q_{LD} represent the quality factor of the micro-ring resonator and LD respectively. The device is fabricated based on low-loss Si3N4 waveguide bringing about a micro-ring Q attaining 2×10^5. Bring the injection power $P_r/P = 0.3$ and linewidth enhancement factor $\alpha = 2.5$ into equation 1, η is estimated to be 1000 showing that the linewidth would be narrowed by 3 orders of magnitude. By altering the voltage on the two pairs of electrodes and the laser's operation temperature, the laser will meet the self-injection equilibrium condition and enter the self-injection locking mode. The principle of laser tuning can be simply explained by filtered optical feedback (FOF) theory [3], since it offers a description of the laser dynamics via two tuning parameters, viz. the centre frequency of micro-ring resonator and its spectra linewidth. This theory draws a conclusion that the detuning frequency of the laser is linear with the tuning frequency of the filter. The process of frequency modulation relies on the TO effect of the waveguide where the heating power on the micro-ring is linear with the detuning resonant frequency enabling a linear sweeping by applying a proper voltage on the electrodes. The results of the static tuning and dynamic frequency modualtion are experimentally demonstrated below.

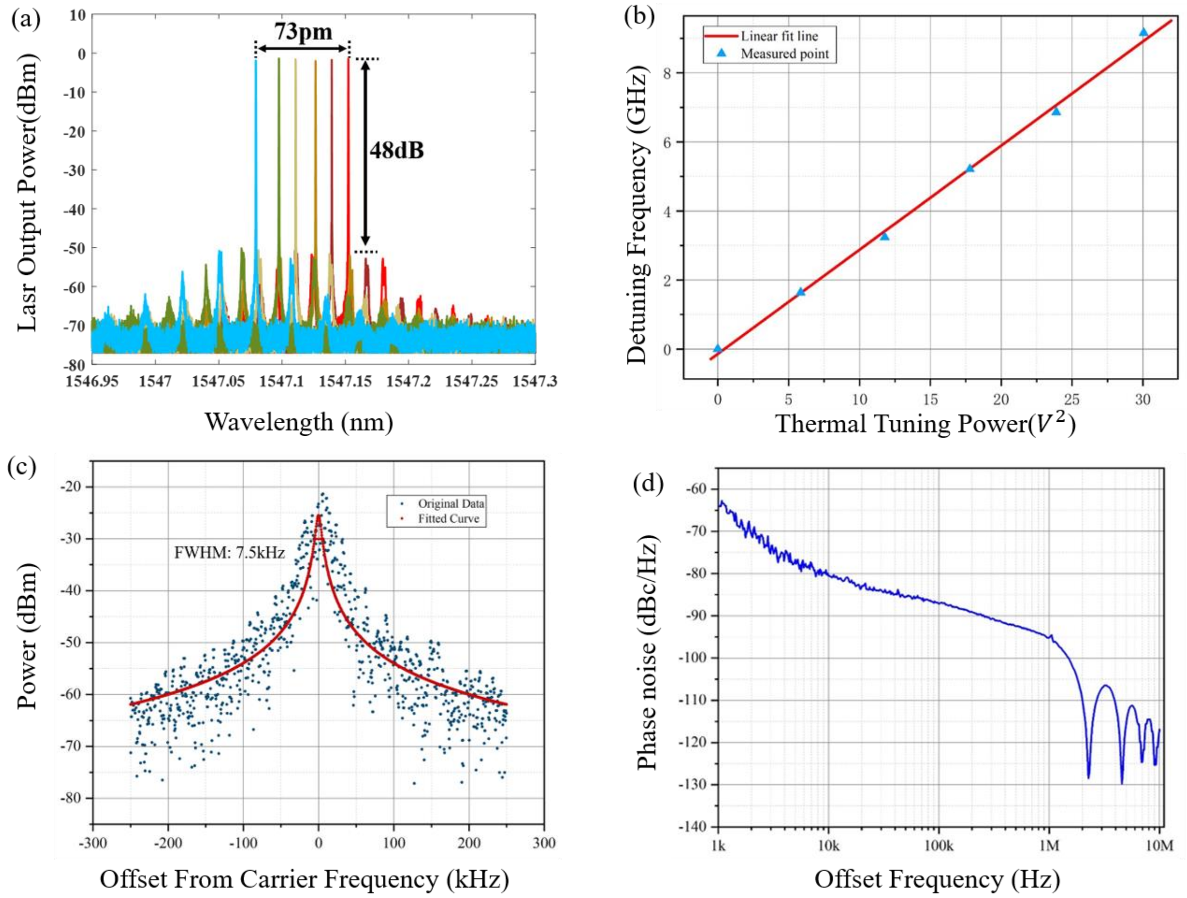

Figure 2. Measurement of the static frequency tuning of the laser. (a)Static frequency tuning with narrow linewidth. (b) Proportional relationship between tuning frequency and thermal power where the red line is a proportional fit of the measured point (blue point). (c) Beat note of 10 km self-heterodyne interferometer with 200 MHz offset by acousto-optic modulator (AOM). The full width at half maximum of the curve is estimated to be 7.5 kHz, so the single laser linewidth is 3.7 kHz. (d) Phase noise of the beat note by 100 m unbalanced MZI.

The DFB laser coupled with external micro-ring resonator is in 14-pin standard butterfly package for practical application. Thermoelectric cooler (TEC) packaged together is applied to maintain a constant temperature. Two electrodes are deposited on the chip for tuning the external roundtrip time and the resonant frequency based on the TO effect. The two-dimensional voltage tuning component allows the laser enter the self-injection locking state after going through the chaotic state and the mode-locked state. Figure 2 shows the self-injection locking state with narrow linewidth and static frequency tuning. By changing the voltage applied on the micro-ring from 8.7 to 9.7 V, 10 GHz frequency tuning was achieved. The linewidth measured by 10 km delayed self-heterodyne interferometer (DSHI) is around 4 kHz among the whole tuning range [4]. The linearity of the detuning frequency

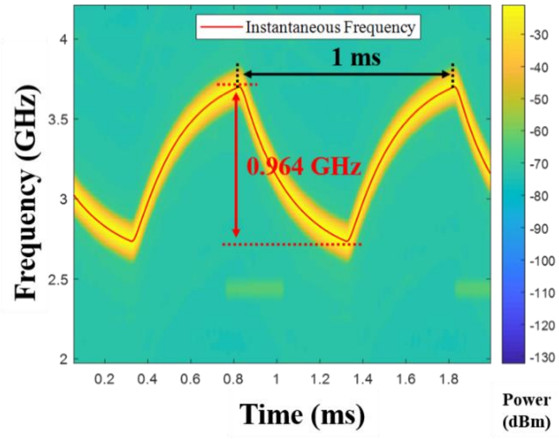

Figure 3. Time-frequency analysis of the beat note by reference laser and FMCW laser.

and the thermal tuning power is well fitted in Fig.2 (b), which make it possible for linear frequency sweeping. In addition, noise analysis is applied using an unbalanced Mach-Zehnder Interferometer (MZI) with a path imbalance (delay line) of 100m. The measured noise spectrum for the laser and the detection noise floor is plotted in Fig .2(d) where the noise shows -65 dBc/Hz at 1 kHz. Frequency modulating is demonstrated in Fig.3 . The continuous static frequency tuning has achieved 10 GHz, making it possible for the FMCW bandwidth to reach 10G. Based on the fact that the thermal power is proportional to the tuning frequency, the square of the voltage applied to the micro-ring is linear with time expecting a linear frequency modulation. Beat note of the FMCW laser and the reference laser is analysed by the time-frequency algorithm to obtain the time-frequency diagram. The frequency modulation based on the thermo-optic has a bandwidth of 0.964 GHz/ms and introduces the linear distortion as shown in Fig. 3.

3. CONCLUSIONS

A frequency sweep laser based on self-injection is proposed. The static tuning range is up to 73pm with 3.7kHz linewidth. Frequency sweeping by TO effect can achieve 0.96GHz/ms and 0.91GHz/25us by PZT driving. The time-frequency domain analysis of the two methods are also compared. The designed laser are in 14-pin butterfly package can be applied in FMCW Lidar.

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REFERENCES

[1] Li Y, Zhang Y, Chen H, et al. Tunable Self-Injected Fabry–Perot Laser Diode Coupled to an External High-Q Si 3 N 4/SiO 2 Microring Resonator[J]. Journal of Lightwave Technology, 2018, 36(16): 3269-3274.

[2] Hinkley E D, Freed C. Direct observation of the Lorentzian line shape as limited by quantum phase noise in a laser above threshold[J]. Physical Review Letters, 1969, 23(6): 277.

[3] Unlocking dynamical diversity: optical feedback effects on semiconductor lasers[M]. John Wiley & Sons, 2005.

[4] Bennetts S, McDonald G D, Hardman K S, et al. External cavity diode lasers with 5kHz linewidth and 200nm tuning range at 1.55 μm and methods for linewidth measurement[J]. Optics express, 2014, 22(9): 10642-10654.