# Multi-Band Linear Frequency Modulation in External Cavity FP-LD Subjected to Multi-Input Injection

Muyoung Lee, Hao Chen, Bikash Nakarmi, *Senior Member, IEEE*, Shilong Pan, *Senior Member, IEEE*, and Yong Hyub Won

***Abstract*— In this letter, we experimentally demonstrate multi-band linear frequency modulation (LFM) signal generation subjected to multi-input optical injection in an external cavity-based Fabry-Pérot laser diode (ECFP-LD). The ECFP-LD is a specially designed FP-LD with a self-injected single longitudinal mode tuned up to 10 nm. The non-linear dynamics in period-one oscillation in ECFP-LD subjected to multi-input optical injection shows unique characteristics for multi-band linear frequency modulation. In the proposed scheme, four external input beams are injected to ECFP-LD, among which one is power modulated with the saw-tooth like waveform, and others are with the constant power. The varying power beam red-shifts the self-injected mode of ECFP-LD and mode-hopping on attaining a particular power level. Hence, multi-band LFM signals are generated by beating self-injected and multi-input injected beams with a large time-bandwidth product (TBWP). The total bandwidths of 12GHz (LFM1: 33-36 GHz, LFM2: 29-32 GHz, LFM3: 25-28 GHz, LFM4: 22-25 GHz) for four-band linear frequency modulation signals with a TBWP of 12000 is measured. The generated multi-band LFM signal provides flexibility on central frequency tunability and dynamic chirp rate for a multi-functional radar system.**

***Index Terms*— External cavity based FP-LD, linear frequency modulation, optical injection, period-one oscillation.**

## I. Introduction

RCENTLY, photonic-assisted linear frequency modulation (LFM) has been the center of attention for multi-functionalities and high-performance radar systems. LFM is widely used for radar systems to achieve long-range detection and high-range resolution due to good pulse compression capability [1]. Traditionally, LFM signals are generated in the electrical domain, including a voltage-controlled oscillator [2], direct digital synthesizer [3], and surface acoustic filter [4]. The electrically generated LFM signal has a low center frequency, small bandwidth, and low-frequency reconfigurability. It limits modern radar applications in distance measurement, recognition of target, and imaging. To overcome the bottlenecks of electronic counterparts, photonic-assisted LFM generation has been proposed for improving frequency range, bandwidth, reconfigurability, and time-bandwidth product (TBWP) [5]–[8]. As modern radar systems demand multi-functionalities and high performance, multi-band radar signals are required rather than single radar signals. Multi-band radar signal can provide higher range resolution and wide detection range than single band radar signal by fusion of multiple frequency bands [9], [10]. Various approaches based on an electro-optic modulator have been proposed to generate a multi-band radar signal [11]–[14]. However, these techniques depend on an electrically generated LFM signal source and hence have a limitation on the center frequency and bandwidth of the generated multi-band LFM signal.

In this letter, we propose a simple configured photonics approach to generate a multi-band LFM signal by injecting a multi-beam to an external cavity-based Fabry-Pérot laser diode (ECFP-LD) Period-one oscillation (P1) state. The ECFP-LD in the P1 oscillation state sequentially red-shift the self-injected mode and then hop the self-injected mode into another mode as the external injection beam strength increases. Among four injected beams, only the first beam's injected power is controlled by an injection strength controller to control the self-injected mode of ECFP-LD in the P1 oscillation state. In contrast, the injection power of others is kept constant. The microwave signal is generated by the beating of the self-injected mode of ECFP-LD and external injected beams. The red-shift of the emission frequency for different mode hopping of the ECFP-LD is also analyzed for the center frequency of multi-band LFM signals. A sequential multi-band LFM signal with a temporal period of 1$\mu$s has been demonstrated. The generated LFM signal has a different chirp rate and a bandwidth of 3GHz. The TBWP of the generated multi-band LFM signal is about 12000.

## II. Operation Principle and Experimental Setup

The FP-LD used in the proposed scheme is specially designed and developed by modifying commercial multi-mode Fabry-Pérot laser diode (MMFP-LD). The inclination of 6° to 8° present on the coupling fiber in MMFP-LD is eliminated, forming an external cavity. The linear wavelength tuning of ECFP-LD of 10 nm and a high side mode suppression ratio (SMSR) was achieved by controlling the operating temperature and biasing current [15].

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Muyoung Lee and Yong Hyub Won are with the Convergence Optoelectronic Device Engineering Laboratory, Electrical Engineering Department, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea (e-mail: muyoung@alumni.kaist.ac.kr; yhwon@kaist.ac.kr).

Hao Chen, Bikash Nakarmi, and Shilong Pan are with the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (e-mail: bikash@nuaa.edu.cn).

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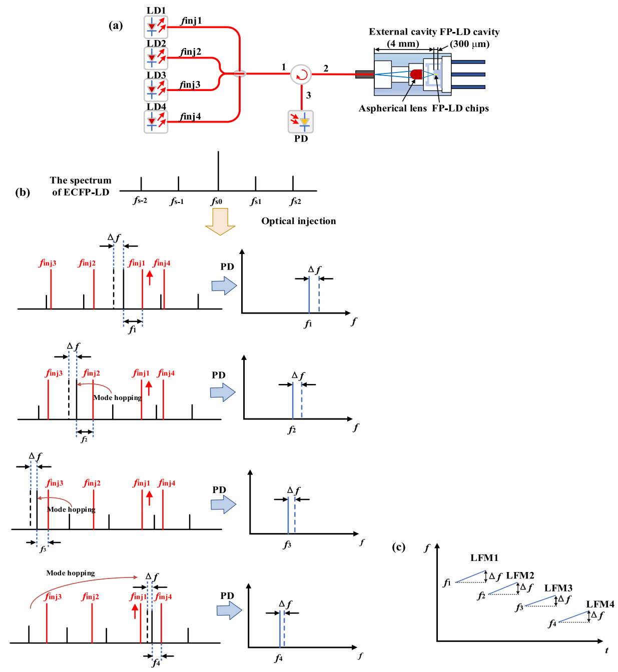


Fig. 1. Principle of multi-input injection to the ECFP-LD for multi-band LFM signal generation. (a) block diagram, (b) microwave signal generation, and (c) time-frequency mapping of multi-band LFM signal.

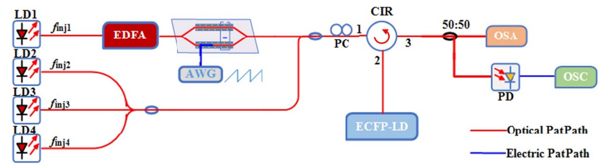


Fig. 2. Experimental setup of multi-band LFM signal generation (LD: Laser diode; PC: polarization controller; EDFA: Erbium doped fiber amplifier; AWG: Arbitrary waveform generator; MZM: Mach-Zehnder modulator; CIR: optical circulator; ECFP-LD: External cavity based Fabry-Pérot laser diode; PD: photoelectric detector; OSA: optical spectrum analyzer; OSC: oscilloscope).

The unique characteristics of P1 oscillation in ECFP-LD with the continuous frequency shift and discontinuous frequency shift of the self-injected mode and microwave generation are shown in our previous research [16]. As the externally injected beam's power increases, red-shift the self-injected mode occurs by antiguidance effect, which is due to reduction in the average charge carrier density and optical gain. The self-injected mode of the ECFP-LD is continuously red-shifted within a matching limit of 3 GHz between the external cavity mode and the internal FP-LD cavity mode which is defined as a continuous frequency shift. Whereas the injected beam's power is increased beyond the red-shift, the self-injected mode vanishes as the mode matching condition is broken for the particular wavelength. Hence, the mode competition occurs for the next self-injected mode known as mode hopping. The mode hopping of self-injected mode to another mode of the FP-LD's internal cavity or external cavity enables discontinuous frequency shift of self-injected mode about 15GHz or 150GHz. Hence, microwave signal generation with large tunability using P1 oscillation in the ECFP-LD is feasible.

Fig.1 (a) shows the simplified block diagram of the proposed scheme where four optical beams from laser diodes with different frequencies, $f_{\text{inj1}}$, $f_{\text{inj2}}$, $f_{\text{inj3}}$, and $f_{\text{inj4}}$, are simultaneously injected into the ECFP-LD. Here, $f_{\text{s0}}$ indicates the frequency of the free-running self-injected mode and $f_{\text{s}-2}$, $f_{\text{s}-1}$, $f_{\text{s}+1}$, and $f_{\text{s}+2}$ indicate the $-2^{\text{nd}}$, $-1^{\text{st}}$, $+1^{\text{st}}$, and $+2^{\text{nd}}$ side mode of the ECFP-LD, respectively. The output of the ECFP-LD is passed through a photoelectric detector (PD) for optical beating to generate the electrical signal. Fig. 1(b) illustrates the injection of four beams to ECFP-LD for microwave signal generation. Among four injected beams, the first beam's injected power is controlled by an injection strength controller, whereas the injection power of the others is kept constant. Therefore, the self-injected mode of ECFP-LD (represented by longer black lines) in the P1 oscillation state is controlled by the first injected beam. The microwave signal is generated by beating the self-injected mode of ECFP-LD (represented by the long black line) and external injected beam (represented by the red line). As the power of $f_{\text{inj1}}$ increases, the emission frequency of the self-injected mode of ECFP-LD is continuously redshifted within the mode matching condition. The first LFM signal is generated as the beating of the first beam and the redshifted self-injected mode. Further increasing the power of $f_{\text{inj1}}$, the mode matching condition is not matched, and mode hopping occurs. Therefore, the next side mode of ECFP-LD, $f_{\text{s}-1}$, becomes a self-injected mode, and continuously redshifted occurs on increasing the power of the injected beam. The second LFM signal is generated by the optical beating of redshifted self-injected mode and $f_{\text{inj2}}$. Similarly, third and fourth LFM signals are generated. Hence, by controlling the power of the first beam, four LFM signals are sequentially generated by the optical beating of the output of the ECFP-LD. By properly controlling the power and the wavelength detuning of the injected beams, a multi-band LFM waveform can be generated, as shown in Fig.1 (c).

## III. The Experimental Setup for Multi-Band LFM Signal

The multi-band LFM generation based on multi-input optical injection to the ECFP-LD is shown in Fig. 2. The reflection rate, threshold current and temperature stability of ECFP-LD are 30%, 12mA, and $0.02^{0}$C, respectively. Four optical beams generated from multi-channel tunable laser diodes are simultaneously injected into the side modes of the ECFP-LD, including the free-running self-injected mode through an optical coupler and an optical circulator. Among four injected beams, one optical beam is amplified by an erbium-doped fiber amplifier (EDFA) and modulated by a Mach-Zehnder modulator (MZM). The beam's injection strength is modulated by a saw-tooth profile control signal generated by an arbitrary waveform generator (AWG). The output of ECFP-LD is analyzed in the optical and electrical domain by an optical spectrum analyzer (OSA) with a resolution of 0.05nm and a real-time oscilloscope (OSC) along with a photodiode (PD) of 40 GHz bandwidth, respectively.

## IV. Experiment Results and Discussion

At first, red-shift and mode hopping of an ECFP-LD are analyzed. The ECFP-LD is operated with a biasing current of 22.4 mA and an operating temperature of 22.7 °C. Under this

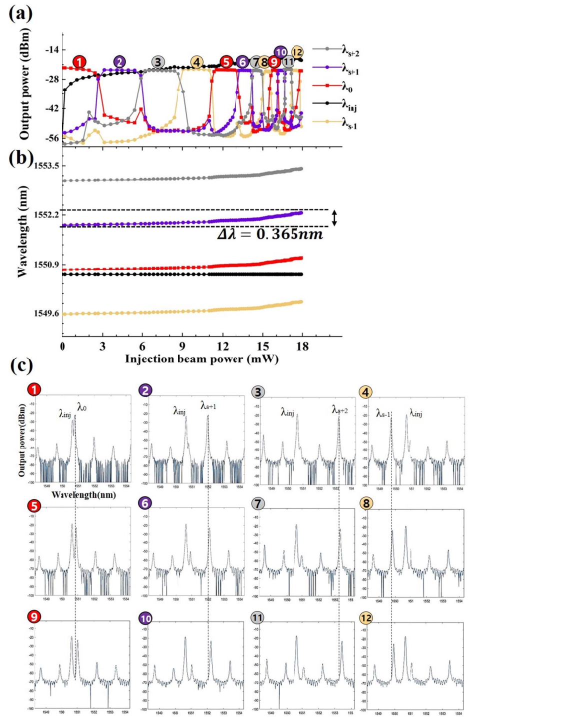


Fig. 3. The characteristics of ECFP-LD with optical injection. (a) Output power, (b) wavelength of FP mode as function of injection beam power, and (c) corresponding optical spectrum.

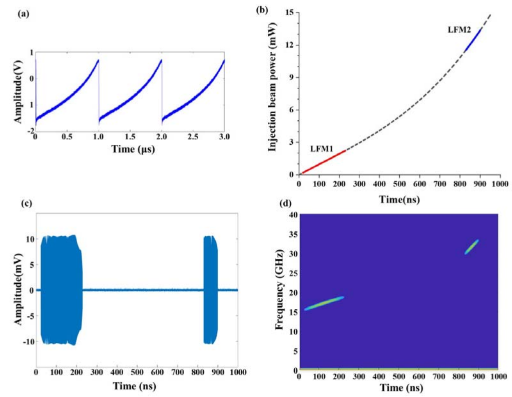


Fig. 4. Experimental result of single beam injection to the ECFP-LD for LFM signal generation. (a) modified saw-tooth signal, (b) injection beam power as function of time, (c) temporal waveform, and (d) frequency-time mapping.

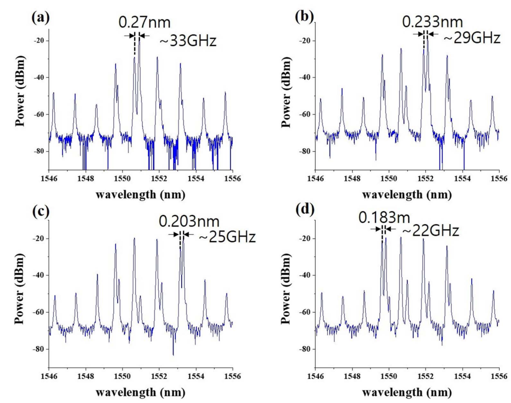


Fig. 5. Optical spectrum of ECFP-LD with four input injection. Beating of (a) 1st input beam, (b) 2nd input beam, (c) 3rd input beam, and (d) 4th input beam and corresponding self-injected mode of ECFP-LD.

condition, the ECFP-LD has a self-injected mode at the wavelength of 1550.79 nm and output power of 0.42 mW, providing an SMSR of 30.9 dB. In the case of single beam injection, it shows characteristics of P1 oscillation, including red-shift and mode hopping of self-injected mode. The external beam is injected into the free-running self-injected mode of ECFP-LD with a negative wavelength detuning of −0.13 nm. Varying the power of the injected beam from 0 mW to 18 mW, the self-injected mode hop from $\lambda_0$ to $\lambda_{S+1}$, $\lambda_{S+2}$, and $\lambda_{S-1}$, as shown in Fig. 3(a). The sequence of mode hopping of the self-injected mode is similar to that reported in [15]. Fig. 3(b) illustrates the red-shift of about 0.365 nm on each mode of ECFP-LD. Fig. 3(c) shows the optical spectrum of ECFP-LD when the power changes from 0 mW to 18mW, corresponding to that of Fig. 3(a). It is seen from Fig. 3(a) and Fig. 3(c) that after multiple hopping, it returns to initial self-injected modes, which is illustrated by the same colored circles (1-5-9, 2-6-10, 3-7-11, and 4-8-12).

Next, one of the injected beam's power is modulated by MZM, governed by the saw-tooth like waveform of AWG, as shown in Fig.4 (a). The signal generated at the output will not be linear with pure saw-tooth waveform, shown in Fig. 4(b). Under external beam injection, the self-injected mode's red-shift is not linear to the injected power. Hence, the control signal is modified from saw-tooth to the one shown in Fig. 4(a) to obtain the linear frequency change. As a result, the LFM signal is obtained by beating the external injection beam and redshifted self-injected mode of ECFP-LD, which is illustrated in Fig. 4. Figure 4(c) shows the temporal waveform of generated LFM signals with 1us measured by OSC. Fig. 4(d) shows the instantaneous frequency-time mapping of the LFM signals. The LFM1 and LFM2 have different center frequencies of 15 GHz and 29 GHz, respectively, and the same bandwidth of 3 GHz. Due to the PD's bandwidth limitation, only the LFM signals generated by the beating of the redshifted free-running self-injected beam and injected beam will be observed at the output. Hence, there is no impact of other injected beams in the output. The LFM1 and LFM2 signals are generated from 20 ns (0.17mW) to 240 ns (2.3mW) and from 830 ns (11.6 mW) to 900 ns (13.1mW), respectively. There is no microwave signal between LFM1 and LFM2, as shown in Fig 4, which is due to the mode hopping of self-injected mode to another side mode as illustrated in Fig. 3(a) and Fig. 3(c). The beating between injected beams is not observed because the bandwidth of PD is limited to 40 GHz. The chirp rate of LFM1 and LFM2 is about 13.63 GHz/$\mu$s and 42.8 GHz/$\mu$s, respectively, defined by frequency shift/time-duration for individual self-injected modes. The different chirp rate of LFM1 and LFM2 is caused by the characteristics of P1 oscillation in ECFP-LD under different wavelength detuning. The TBWP of the generated LFM signal is calculated to be 6000.

Fig. 5 shows the injection of four optical beams at $\lambda_{S0}$, $\lambda_{S+1}$, $\lambda_{S+2}$, and $\lambda_{S-1}$ with a wavelength detuning of −0.27 nm, −0.233 nm, −0.203 nm and −0.183 nm, respectively and the mode hopping of self-injected beam on increasing the power of $f_{inj1}$. On increasing the power of the injected

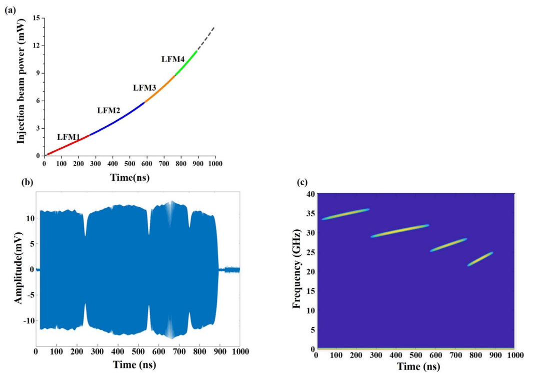


Fig. 6. Experimental result of multi-input beam injection to the ECFP-LD for multi-band LFM generation. (a) injection beam power as function of time, (b) temporal waveform, and (c) frequency-time mapping.

beam $f_{\text{inj1}}$, the red-shift of the self-injected mode followed by mode hopping is observed. Fig. 5 (a), (b), (c), and (d) illustrate the output of ECFP-LD with four beams injection with the free-running self-injected mode at $\lambda_{S0}$ at first and then mode hopping to $\lambda_{S+1}$ to $\lambda_{S+2}$, and $\lambda_{S-1}$ when the power of the injected beam is 0.17 mW, 2.3 mW, 5.74 mW, and 8.66 mW, respectively. We noticed that the 3$^{\text{rd}}$ hopping of self-injected mode shift went backs to the initial self-injected mode, which matched that of the property of ECFP-LD [15].

The self-injected mode experiences red-shift of about 3 GHz with an increase in the injected beam's power. As a result, an LFM signal with a bandwidth of 3GHz is observed with every self-injected beam. The first LFM signal is observed with the starting frequency of 33 GHz, equivalent to the wavelength detuning of 0.27 nm. Further increase in the injected beam's power, the self-injected mode hops to first side mode, $\lambda_{S+1}$, and again experiences a red-shift of 3 GHz. As a result, an LFM signal with a starting frequency of 29 GHz and the same bandwidth of 3 GHz is observed. Similarly, an LFM signal with starting frequencies of 25 GHz and 22 GHz and a bandwidth of 3 GHz is observed.

Figure 6 illustrates the multi-band LFM generation with four injected beams Fig. 6(a), (b), and (c) shows the injection beam power as a function of time, temporal waveform and the time-frequency mapping, respectively. The LFM1, LFM2, LFM3, and LFM4 signals have the starting frequencies of 33 GHz, 29 GHz, 25 GHz, and 22 GHz with 3 GHz bandwidth. The LFM signals have different chirp rates due to the non-linear chirp rate of the P1 state. With an increase in the injected beam's power, the chirp rate also changes, as shown in Fig. 3(a). The LFM1, LFM2, LFM3, and LFM4 signals are generated from 20 ns (0.17mW) to 270 ns (2.3mW), 270 ns (2.3 mW) to 570 ns (5.74 mW), 570 ns (5.74 mW) to 760 ns (8.66 mW), and 760 ns (8.66 mW) to 890 ns (11.4 mW), respectively. The corresponding chirp rates are 12 GHz/$\mu$s, 10 GHz/$\mu$s, 15.8 GHz/$\mu$s, 23.1 GHz/$\mu$s, respectively. The TBWP of the generated LFM signal is calculated to be 12000.

## V. Conclusion

This paper proposed and experimentally demonstrated multi-band LFM signal generation using multi-input injection to the ECFP-LD in the P1 oscillation state. The self-injected mode of ECFP-LD is continuously redshifted and followed by mode hopping on varying the power of the first external injected beam. The beating of redshifted self-injected mode and the corresponding external injected beam generates LFM signals. Each generated LFM signal has a bandwidth of 3 GHz with a total bandwidth of 12 GHz in the temporal period of 1$\mu$s and the TBWP of 12000. Each LFM signal has a different chirp rate due to P1 characteristics of ECFP-LD. The center frequencies of each LFM signal can be varied by changing the frequency detuning of injected beams. Therefore, the multi-band LFM signal generation with ECFP-LD provides flexibility on the independent tuning of center frequencies of LFM signals with different chirp rates. With these advantages of demonstrated multi-band LFM signals, the proposed scheme can be used for next-generation multi-functional radar systems.

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