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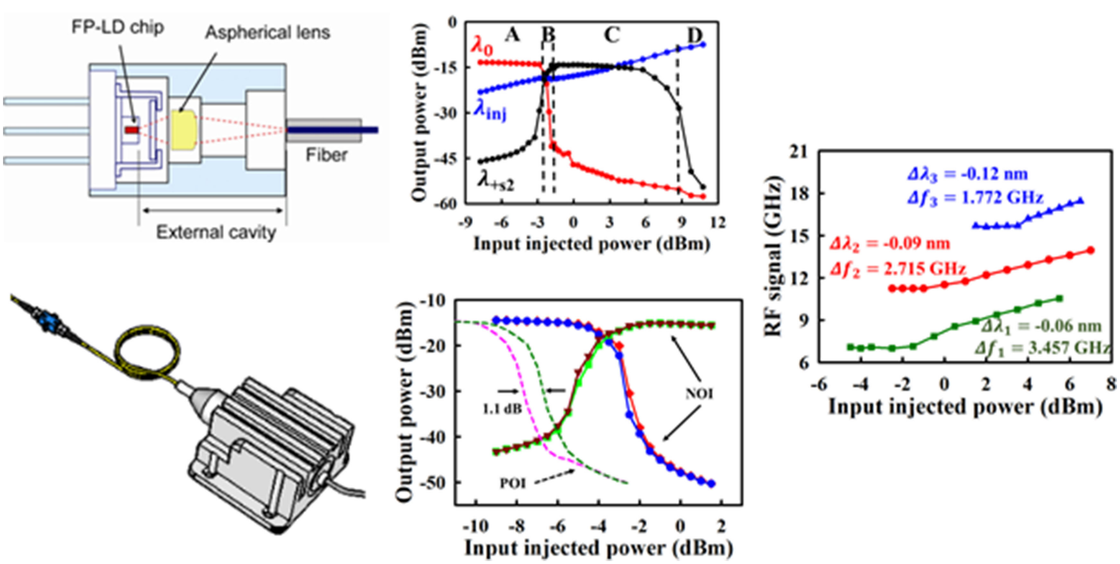

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Optical Behavior Analysis of Negative Wavelength Detuning in SMFP-LD and Its Effect on Multi-RF Generation

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Abstract: Injection locking with positive wavelength detuning has been used for a long time for optical signal processing, signal generation, and computing. Recently a new technique, “injection locking with negative wavelength detuning,” has been introduced and has shown its potential on microwave generation. In this paper, we analyze optical behavior of negative injection locking and its impact on multi-RF generation using single-mode Fabry-Pérot laser diode (SMFP-LD). SMFP-LD is composed of a commercial multi-mode FP-LD with a built-in external cavity. As compared to conventionally used positive detuning optical injection, the negative detuning optical injection (NOI) shows advantageous differences on the suppression of the dominant mode, side modes, bistability property, and the hysteresis width. The laws of free carrier motion in the laser cavity is leveraged to explain these phenomena. Based on the analysis, the NOI in the SMFP-LD has a distinct advantage for multi-RF generation and switching RF signals. In addition, the output performances of the generated RF signal such as linewidth, power-dependent frequency shifting, and signal-to-noise ratio (SNR) are investigated.

Index Terms: SMFP-LD, negative wavelength optical injection, bistability, multi-RF generation.

1. Introduction

Optical injection in semiconductor lasers has been widely studied for chaos and locking [1], [2], microwave photonics [3]–[6], and digital signal processing [7], [8] leveraging various dynamics in laser cavity. Among these, the generation of RF signals using optical injection in semiconductor laser has received tremendous concern due to simple structure, tunable range, flexibility in configuration and low cost [9]. Optical injection locking in semiconductor lasers can be obtained in two ways: positive detuning optical injection (POI) and negative detuning optical injection (NOI). The POI/NOI refers to the injection of an external beam with longer/shorter wavelength compared to the nearest laser mode, whether that is dominant mode or any of the side modes of the laser diode. Both

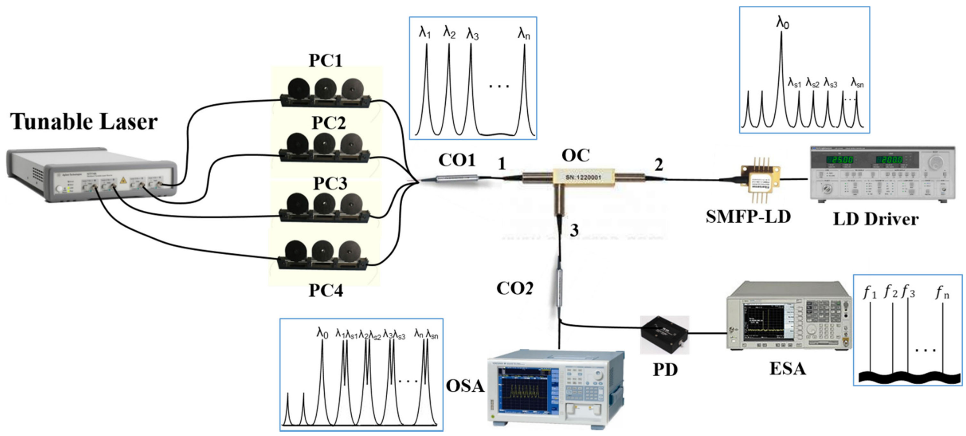

Fig. 1. Experimental setup of the RF signal generator based on an SMFP-LD with NOI.

POI and NOI can be applied for RF signal generation. However, most of the previously reported approaches for RF signal generation are limited to single RF signal generation [10]. Recently, we observed multi-RF signal generation in a single-mode Fabry-Pérot laser diode (SMFP-LD) with NOI [11]. However, the detailed analysis of laser modes in terms of optical power and wavelength, hysteresis width that affects the rising and falling time for switching and their influence on single and multi-RF generation are not investigated yet.

In this paper, NOI in an SMFP-LD is experimentally analyzed, which includes (1) the power variation and wavelength shifting of the laser modes as a function of the power of the externally-injected beam, (2) the bistability property and hysteresis width of the dominant mode and the operating side mode of the SMFP-LD, and (3) the performance of single and multi-RF generation using NOI in terms of linewidth, power dependent frequency shifting, signal-to-noise ratio (SNR). Based on the analysis, we present the insight of multi-RF signal generation, frequency tuning, and switching of the generated RF signals using a single SMFP-LD and compared with that of POI. The analysis can lead to flexible and cost-effective RF signals generation and fast switching required for reconfigurable multi-functional radars [12], multi-beam satellite communications [13], 5G mobile communication and networks, and other applications.

2. Experimental Setup and the SMFP-LD

Fig. 1 shows the experimental setup for the analysis of NOI in terms of bistability, hysteresis width, output signal quality of RF generator, multi-RF generation and switching in a single SMFP-LD. External beams from a tunable laser are injected to SMFP-LD through polarization controllers (PCs), an optical fiber coupler (CO1) and an optical circulator (OC). PCs are used to control the polarization state of the external injected beams because the injection locking with gain modulation in SMFP-LD only works with TE mode of the injected beam. With TM mode, SMFP-LD shows the behavior of absorption null known as absorption modulation [14]. Laser diode driver is used to control the bias current and operating temperature of the SMFP-LD for single longitudinal mode oscillation and wavelength tuning of the dominant mode. The output of the SMFP-LD obtained through OC is further divided into two paths by a 50:50 optical coupler (CO2) for the signal analysis in optical and electrical domain.

The key component in the experiment is the SMFP-LD, which is composed of a multi-mode FP-LD with a built-in external cavity. Due to the Vernier effect of the external cavity, a single longitudinal mode with 34-dB side mode suppression ratio (SMSR) can be attained by controlling the temperature and bias current via a laser driver [15]. The operating principle and other characteristics of SMFP-LD and multi-mode FP-LD are similar except the dominant mode that is present in

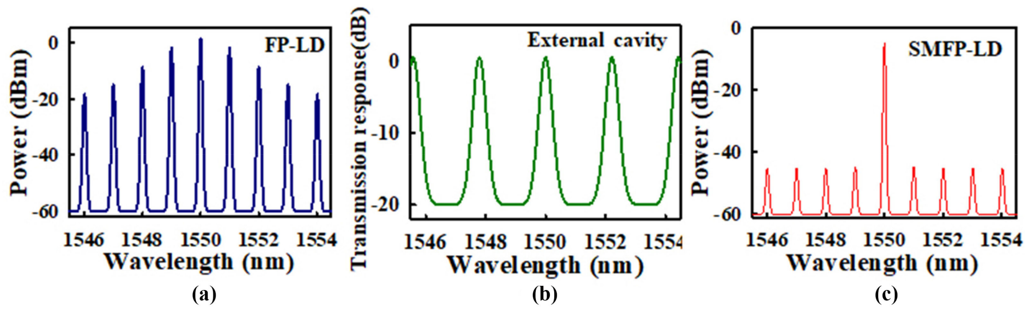

Fig. 2. The simulated (a) optical spectrum of the multi-mode FP-LD, (b) the transmission response of the external cavity, and (c) the optical spectrum of the SMFP-LD.

SMFP-LD. Mathematically, the overall gain G of the SMFP-LD can be written as [16], [17]

$$G = G_{\text{ic}} \times G_{\text{ec}} = \frac{T v_g a(n - n_0)}{\left\{\left[1 + \left(\frac{2i\Delta f_{\text{mode}}}{\Delta f_{3\text{dB}}}\right)^2\right]\right\} \cdot \left[1 + \varepsilon \sum_m S_m\right]} \times \frac{G_0}{1 + {G_0}^2 R_1 R_2 - 2G_0\sqrt{R_1 R_2}\cos\beta} \tag{1}$$

where, G_{ic} and G_{ec} represent the gain of the internal and external cavities, respectively, T is the confinement factor, v_{g} is the group velocity of the laser modes, a is the gain modeling parameters, n is the carrier density, n_0 is the transparent carrier density, i is the mode number counted from the central mode ($i = 0$), Δf_{mode} is the mode space of the wavelength, $\Delta f_{3\text{dB}}$ is the 3-dB bandwidth of each mode, ε is the gain compression factor, and S_m is the photon density of m$^{\text{th}}$ mode. G_0 is the single-pass gain of the external cavity, R_1 and R_2 are reflectivity of the end face of the FP-LD and the optic fiber pigtail, respectively, $\beta = 4\pi\frac{L_{\text{ec}}}{\lambda} + 2\pi$ is the phase difference of the light, L_{ec} is the external cavity length, and λ is the wavelength.

Based on (1), the simulated output spectrum of the SMFP-LD is shown in Fig. 2. With a proper external cavity length, one of the FP-LD modes can be matched with the external cavity mode, as illustrated in Fig. 2(a) and (b). Due to the different free spectral range (FSR) of the two cavities, only the longitudinal mode at one mode which is 1550 nm for this simulation exist in the SMFP-LD, and all other modes are suppressed, as shown in Fig. 2(c). The side mode suppression ratio of more than 30 dB is obtained. The output spectrum is matched with that of the SMFP-LD fabricated with external cavity, which has only one self-injected mode. Further changing the temperature, the self-injected mode can be tuned to another mode.

3. Experimental Result and Discussion

Fig. 3 illustrates the effect of injected beam power with POI and NOI on the power of the dominant mode, side modes, and wavelength of the modes of SMFP-LD. At first, we analyzed the effect of injected beam power on dominant mode, side modes, and wavelength of the modes of SMFP-LD with NOI. We injected an external beam (λ_{inj}) into $+2^{\text{nd}}$ side mode ($\lambda_{+\text{s}2}$) of the SMFP-LD with a negative wavelength detuning ($\Delta\lambda$) of -0.09 nm. With the increase of injection beam power, the injection locking phenomena can be divided into four regions (A, B, C and D) as shown in Fig. 3(a). Region A: weak injection, where the power of the dominant mode (λ_0) decreased slightly with increase in power of the input injected beam. In addition, the gradual increase of the power of side mode $\lambda_{+\text{s}2}$ is observed with increase in the power of the injected beam unlike to that of POI, where there is no increase in the power of the side mode, as illustrated in Fig. 3(b) by blue solid line (NOI) and red dotted line (POI). Region B: moderate injection, where the injected power was not sufficient to suppress λ_0, but $\lambda_{+\text{s}2}$ was adequately motivated to oscillation, as shown in Fig. 3(c) (blue line). Whereas for POI, the corresponding side mode shifts to the injected beam with increase

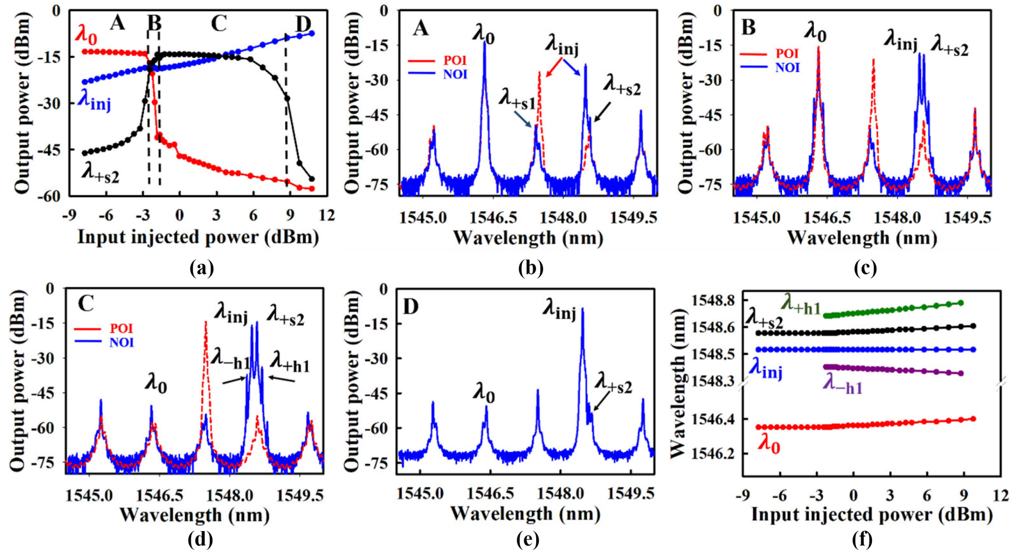

Fig. 3. Experiment analysis of the NOI and POI in SMFP-LD: (a) output power variation of the dominant mode (red line), the $+2^{nd}$ side mode (black line) and the injected beam (blue line) with NOI (b) weak injection with NOI and POI, respectively (c) moderate injection with NOI and POI, respectively (d) strong injection with NOI and POI, respectively (e) ultrahigh injection with NOI (f) wavelength variation with NOI.

in the injected beam power. Region C: strong injection, where λ_0 was suppressed with a contrast ratio of more than 40 dB as shown in Fig. 3(d) (blue line), and significant four-wave mixing (FWM) between λ_{inj} and λ_{+s2} is observed. Region D: ultrahigh injection region in which λ_0 and λ_{+s2} are all suppressed due to the strong power of the λ_{inj}, as shown in Fig. 3(e).

Next, we analyzed the case of POI with respect to the injected power, which can be divided into two parts: (1) Weak injection: In this case, the injected power is not sufficient to suppress the dominant mode and hence two beams exist in the laser cavity, represented with red lines in Fig. 3(b) and (c). (2) Strong injection: In this case, the dominant mode is suppressed with high contrast ratio and only the injected beam exists in the cavity, as shown in Fig. 3(d) (red line). Due to the strong stimulated emission generated by the injected beam, it leads to the reduction of the free carrier density in the active region of the laser cavity. As a result, the gain of the dominant mode decreases below the oscillation threshold of the cavity. Moreover, the effective refractive index reduces as the free carrier density decreases, so all the modes of the SMFP-LD shift to longer wavelength until the nearest side mode coincides with the injected beam, leading to injection locking. We noted that with POI, regions B and C could not be achieved. Hence, with POI only a single RF generation is possible with single beam injection. However, injection with NOI, simultaneous microwave (optical beating between injected beam and the corresponding side mode) and millimeter wave (optical beating between injected beam and the dominant mode) can be obtained with single external beam. In addition, hoping from one RF to another RF can be easily acquired with change in the injected beam power in NOI. Fig. 3(f) shows the wavelength variation of the laser modes as a function of the injected power, which verifies that with NOI, the wavelength variation on the dominant mode and the corresponding side mode are more constant to that of POI. In Fig. 3(f), we also observe that two harmonics (λ_{+h1} and λ_{-h1}) are generated in NOI due to FWM between λ_{inj} and λ_{+s2}, whereas no FWM is observed in POI because no corresponding side mode exist in POI as red shift occurs in POI. The FWM is significant in NOI when the input injected power is from -2 to 9 dBm. Prior to this range, the injected beam power contributes on the power gain of the corresponding side mode whereas beyond 9 dBm, the SMFP-LD enters to the ultrahigh injection region. In ultrahigh injection, the power of injected beam λ_{inj} lead to significant reduction of the cavity carrier density resulting decrease in the gain of all the modes to the threshold. As a result, both λ_0 and λ_{+s2} are suppressed.

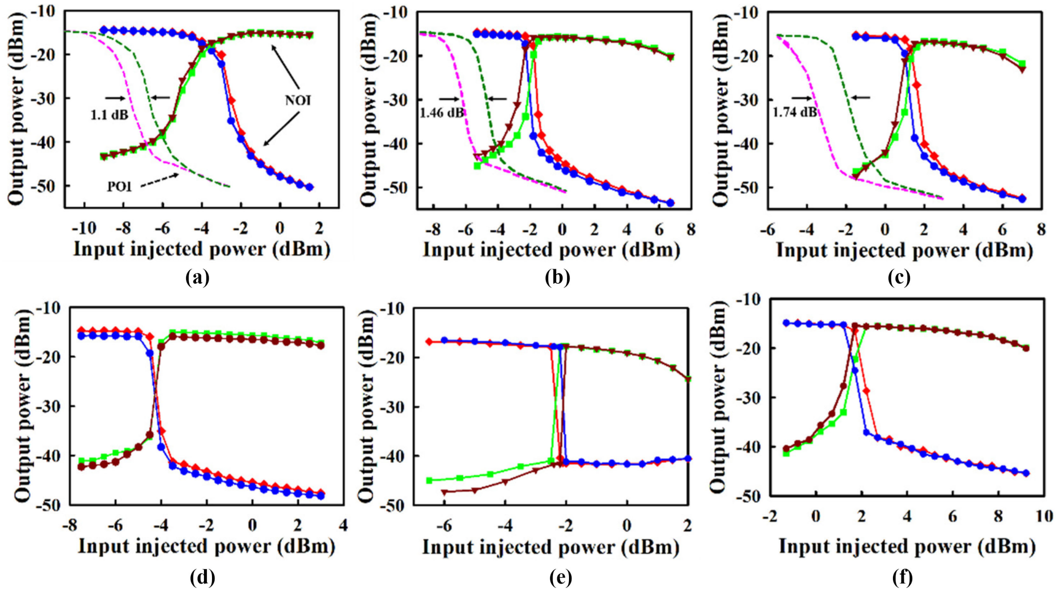

Fig. 4. Bistability properties analysis of the POI and NOI in the SMFP-LD. Red and blue solid lines represent the case of the dominant mode and brown and green for the side modes of the NOI; the pink and dark green dotted line represent the case of the dominant mode of the POI. (a) $\Delta\lambda = -0.06$ nm and injected to λ_{+s1}; (b) $\Delta\lambda = -0.09$ nm and injected to λ_{+s1}; (c) $\Delta\lambda = -0.12$ nm and injected to λ_{+s1}; (d) $\Delta\lambda = -0.06$ nm and injected to λ_{+s2}; (e) $\Delta\lambda = -0.09$ nm and injected to λ_{+s2}; (f) $\Delta\lambda = -0.12$ nm and injected to λ_{+s2}.

On the other hand, increasing the power of the injected beam reduces the cavity carrier density and therefore decrease the effective refractive index, so the frequencies of the modes decrease and, resulted in a red shift [18], as shown in Fig. 3(f). Hence, from Fig. 3, we can conclude that the main difference between POI and NOI with respect to the injected beam power is on the power and wavelength variation of the side mode where the external beam is injected, λ_{+s2}.

We also experimentally investigated the injection of external beam to different side modes of SMFP-LD with different wavelength detuning, which shows the similar results as shown in Fig. 3(a) with four different regions irrespective to the modes and wavelength detuning. The only difference with different wavelength detuning is the power requirement, which is directly proportional to wavelength detuning as in POI for obtaining four regions with NOI.

Next, we analyzed the bistability property and hysteresis width of the dominant mode and the corresponding side mode with the NOI. We injected the λ_{inj} at $+1^{st}$ (λ_{+s1}) and $+2^{nd}$ side mode (λ_{+s2}) with $\Delta\lambda = -0.06$ nm, -0.09 nm and -0.12 nm. The red and blue solid lines in Fig. 4 are the respective power of λ_0 when the injected power is first increased until λ_0 is suppressed with a contrast ratio of 35 dB and then decreased until the suppressed dominant mode is released. Whereas the green and brown solid lines represented for that of the corresponding side mode. The pink and dark green dotted lines are the power variation of λ_0 with the same wavelength detuning in the POI. The bistability curve of the corresponding side mode with POI is not shown, because in POI, no bistability is observed for corresponding side mode. In POI, the corresponding side mode, where the injected beam is injected, shifts to the injected beam due to the red shift occurs in POI with increase in the power of injected beam. Fig. 4(a), (b) and (c) show the output power of λ_0 and λ_{+s1} mode with $\Delta\lambda = -0.06$ nm, -0.09 nm and -0.12 nm, respectively. Similarly, Fig. 4(d), (e) and (f) show the power variation of λ_0 and λ_{+s2} mode with $\Delta\lambda = -0.06$ nm, -0.09 nm and -0.12 nm, respectively. From Fig. 4, we observed that NOI in SMFP-LD behaves a bit different from that of the POI in terms of optical bistability. Almost no hysteresis width is present with $\Delta\lambda = -0.06$ nm and the hysteresis width increased from 0.44 dB to 0.56 dB when $\Delta\lambda$ changed to -0.09 nm and -0.12 nm whereas in the POI, the increment in the hysteresis width is about 1 dB for the same.

TABLE 1
RF Generation Using Optical Injection in the SMFP-LD

RF Signal / Optical Injection	Millimeter-wave signal only	Micro/Millimeter wave signals	Microwave Signal only
Positive optical injection	√ (Weak injection)	× (dominant mode suppressed)	√ (dominant mode suppressed)
Negative optical injection	√ (Weak injection)	√ (Moderate injection)	√ (Strong injection)

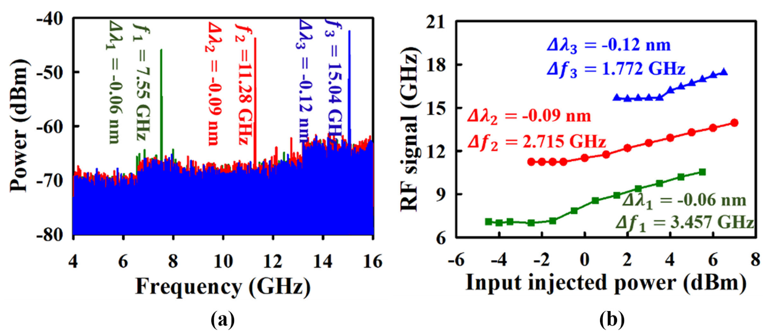

Fig. 5. (a) The RF signal generated by the NOI with different wavelength detuning. (b) The RF frequency as a function of the increased injected power of the external beam.

The hysteresis width is given by the difference in input injected beam power that is required for the suppression of λ_0 and the power required for releasing λ_0 on decreasing the injected power. Fig. 4 shows that although the SMFP-LD with NOI has exhibited the bistability effect, the hysteresis width is much smaller than that in the POI. The narrow hysteresis width benefits in RF signal generators and RF hopping since in NOI, the hysteresis width is very narrow and slightly increase with increase in wavelength detuning unlike in POI.

Further, we experimentally investigated the RF generation with POI and NOI using SMFP-LD. With POI, either millimeter-wave or microwave signal can be generated with weak injection locking depending on whether the beam is injected to the dominant mode or any of the side modes, respectively. Whereas, from Fig. 3, we can see that using NOI in the SMFP-LD, the generation of millimeter-wave [Fig. 3(b)] to simultaneous microwave and millimeter wave [Fig. 3(c)] to microwave [Fig. 3(d)] can be obtained by changing the injected beam power. Table 1 summarizes the generation of RF signal using optical injection with the POI and NOI.

Fig. 5(a) shows the electric domain spectrum result of the generated microwave signals when the external beam is injected to λ_{+s2} with $\Delta\lambda = -0.06$ nm, -0.09 nm, and -0.12 nm. The linewidths of the microwave signals are 2.66 MHz, 2.82 MHz and 2.91 MHz, for the RF signal of 7.55 GHz, 11.28 GHz and 15.04 GHz, respectively, where the resolution bandwidth (RBW) of the ESA is 100 kHz. The minimum SNR and the power variation of the generated RF signal are 20 dB and within the range of 1 dB. The generated RF signals are tunable and can obtained by changing the wavelength detuning. Hence, RF generation with NOI in SMFP-LD can be used for different targeted applications.

The frequency of the generated microwave signals are stable with increase in injected power below a certain value (~ -2 dBm for $\Delta\lambda = -0.06$ nm, ~ -1 dBm for $\Delta\lambda = -0.09$ nm, and ~ 4 dBm for $\Delta\lambda = -0.12$ nm). With further increase in power of the injected beam beyond this, the wavelength spacing between the injected beam and the nearest side mode increased due to the red shift of the modes in the laser cavity. Therefore, the frequency of the RF signal increases linearly to that of the external beam power, as shown in Fig. 5(b). The maximum frequency shift with increase in

TABLE 2
Minimum Injected Power for the RF Generation With $\Delta\lambda = -0.09$ nm Under Moderate Injection Locking Region

Number of beams \ injected Power required for side mode	λ_{s1} mode (dBm)	λ_{s2} mode (dBm)	λ_{s3} mode (dBm)	λ_{s5} mode (dBm)
Single beam injection	-2.13	-2.25	-2.09	-2.06
Two beams injection	-4.13	-4.02		
	-4.06		-4.10	
	-4.04			-4.05
		-4.06	-4.10	
		-4.07		-4.04
			-4.04	-4.05
Three beams injection	-5.86	-6.03	-5.91	
	-5.89	-6.04		-6.14
	-5.86		-5.93	-6.14
		-6.09	-5.92	-6.12
Four beams injection	-7.79	-7.61	-7.69	-7.41

the injected beam power are 3.457 GHz for $\Delta\lambda = -0.06$ nm, 2.7152 GHz for $\Delta\lambda = -0.09$ nm and 1.772 GHz for $\Delta\lambda = -0.12$ nm before SMFP-LD operates in region D, shown Fig. 3(a). This linear shift in frequency of the generated RF signal can be utilized as a tuning characteristics of RF signal with changes in the input injected power. The maximum tuning range that can be obtained with RF generation with power variation is inversely proportional to the wavelength detuning which is seen in Fig. 5(b).

One of the key advantages of SMFP-LD for RF signal generation is the capability of handling multiple beams injection with NOI that can be used for multi-RF generation, which is difficult to obtain in other semiconductor laser diodes [11]. In the experiment, we analyzed the minimum power required for injected beams to generate multi-RF with the NOI in the SMFP-LD under moderate injection locking, which are summarized in Table 2.

At first, only a single external beam is injected to $+1^{st}$, $+2^{nd}$, $+3^{rd}$, or $+5^{th}$ side mode of the SMFP-LD with $\Delta\lambda = -0.09$ nm in order to analyze the minimum power required for the microwave generation under moderate injection locking. We observed that irrespective to the side mode where the external beam is injected, the minimum power required for RF signal generation is almost constant (around -2.10 dBm). Further, we increased the number of injected beams from one to two, three and four beams to analyze the variation on minimum power required for the microwave generation with same $\Delta\lambda$ in multi-input injection scenario. We found that with increase in number of injected beams, the minimum power required for generating multi-RF signal decrease from -2.10 dBm to -4.06 dBm, -6.03 dBm and -7.69 dBm for two, three and four beams injection, respectively. Table 2 also shows that irrespective to the order of the side modes where the external beams were injected, the minimum power required for generating microwave signal corresponding to the same $\Delta\lambda$ was almost the same for multiple beams injections. In addition, it is possible to generate multi-RF signals with different $\Delta\lambda$ injected to different side modes of the SMFP-LD, which is illustrated in Fig. 6. With change in $\Delta\lambda$, the power required of the injection locking changes proportionally. Fig. 6(a) shows the optical spectrum of simultaneous three-beam injection with $\Delta\lambda_1 = -0.06$ nm, $\Delta\lambda_2 = -0.09$ nm, and $\Delta\lambda_3 = -0.12$ nm which gives three RF signals of frequencies 7.89 GHz, 11.26 GHz, and 14.99 GHz, as shown in Fig. 6(b). the higher frequencies due to the beating between dominant mode and injected beams and injected beams are not seen due to the limitation of the PD bandwidth and the ESA (maximum measurement of ESA used is of 43 GHz). We measure the SNR, linewidth and power fluctuation for the duration of 1 hour of the generated

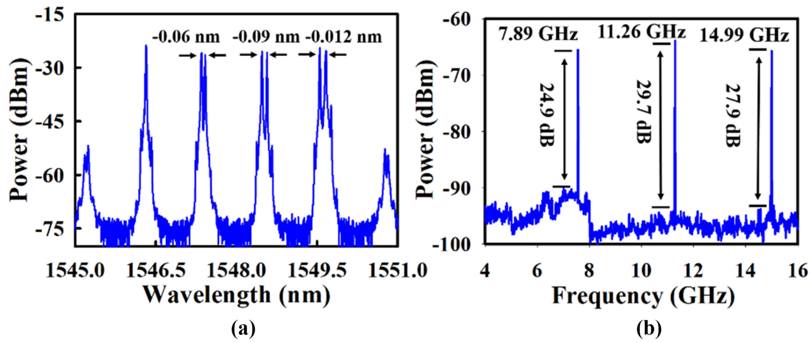

Fig. 6. Multi-band RF generation using an SMFP-LD with multi-beam NOI. (a) optical spectrum (b) electric spectrum.

electrical RF signals which are 24.9 dB, 29.7 dB, and 27.9 dB and 2.63 MHz, 2.80 MHz and 3.1 MHz, respectively for 7.8 GHz, 11.26 GHz, and 14.99 GHz. The power fluctuation of the RF signals are measured below 1 dB within the interval of 1 hr.

4. Conclusion

In conclusion, we analyzed the optical behavior of NOI in SMFP-LD in terms of input injected beam power, wavelength detuning, number of injected beams to the power of dominant mode, side modes, bistabiltiy and hysteresis width, and the generation of multi-RF signal in a single SMFP-LD. Depending on the power of injected beam, four injection states existed in the NOI: (1) weak injection, (2) moderate injection, (3) strong injection and (4) ultrahigh injection. The optical bistability in NOI is also analyzed, which shows a negligibly narrow hysteresis width, indicating that NOI is more efficient for RF signal generation. We also measured the NOI characteristics for RF generation in the SMFP-LD. Based on the analysis, NOI provides advantages on RF signal performances such as large tuning range, and simultaneous multi-RF generation compared to that of POI. In addition, due to negligible amount of hysteresis width present in NOI, the switching from one RF to another can be achieved in higher speed with less rising and falling time. Generation and switching of millimeter wave, simultaneous microwave and millimeter wave, and microwave are possible with NOI, while they are not possible with the POI. In addition, we analyzed the capability of multi-RF generation with NOI in a single SMFP-LD and the required minimum injected power for single and multi-RF generation. The required power for the generation of RF signal is almost same regardless of the side modes where the external beams are injected. Another parameter analyzed is RF frequency shift in terms of the power of the injected beam while the SMFP-LD under ultrahigh injection. We concluded that the frequency variation that can be obtained with change in the injected beam power is inversely proportional to the wavelength detuning. The analysis of NOI for the generation of RF signals are useful on the generation of simple, flexible, stable and reconfigurable multi-RF signals for 5G mobile networks, reconfigurable multi-functional radars, multi-beam satellite communications and other applications. The analysis of phase noise with single and multiple RF signals can be additional parameter to confirm the quality of the generated RF signal which we will carry out on future research works.

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