Simultaneous Generation of Multiband Signals Using External Cavity-Based Fabry–Perot Laser Diode

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***Abstract*— Photonic generation of tunable microwave signal has gained the attention of many research communities. Various active components such as vertical-cavity surface-emitting laser diode, semiconductor optical amplifier, and Fabry–Perot laser diode have been used for generating microwave signals using different techniques including side mode injection, feedback injection, and frequency combs. In this paper, we propose and demonstrate a novel approach to generate millimeter wave, simultaneous microwave and millimeter wave, and microwave together with hopping of RF frequency using a single external beam. Furthermore, we demonstrate injecting multiple external beams in a spatial-mode Fabry–Perot laser diode (SMFP-LD) to generate simultaneous multiband signals with negative wavelength detuning. The generated signal ranges from microwave to terahertz. We inject four external beams in SMFP-LD to generate RF frequencies that lie in Ku-, K-, Ka-, V-bands and higher millimeter wave. The frequency of generated signals can be tuned from a few gigahertz to several terahertz. The effects of changing the dominant mode, injecting external beams to different side modes, wavelength and power stability of beating wavelengths, and harmonic generations are analyzed. The maximum linewidth of the generated RF signals with multiple input beams (up to 42.5 GHz) is found to be about 300 kHz.**

***Index Terms*— Microwave photonics, single-mode Fabry–Perot laser diode, wavelength detuning.**

I. Introduction

PHOTONICS microwave signals have been extensively researched and applied in optical wireless networks [1], [2], 5G mobile communications [3], radio-over-fiber communication [4], photonic microwave signal processing [5], photonic microwave beamforming [6], satellite telecommunication system [7], and several other fields [8]–[11]. In recent years, photonic generation of microwave signal has gained much attention as it offers prominent advantages such as low cost, compact device size, and wide tunable range compared to traditional electronic techniques [8], [11]–[14]. Various optical methods using semiconductor lasers for generating microwave signals have been presented in recent reports. Optical heterodyne detection [15], dual-mode lasing emission [16], and external optical injection [17] have often been adopted, as these methods offer high-density integration, low power consumption, and broad tuning range. Compared to semiconductor lasers such as multimode lasers, quantum dot lasers, vertical-cavity surface-emitting lasers combined by grating and multireflectors, and fiber ring lasers [18]–[22], spatial-mode Fabry–Perot laser diode (SMFP-LD) has several competitive advantages and unique characteristics. SMFP-LD offers self-locking mode, low threshold current, high side-mode suppression ratio (SMSR), wide tunable range, multiple external beam handling capability, and simple structure [23]. Due to these features, SMFP-LD is used for realizing various optical functions such as wavelength conversion, logic gates, optical switching, and optical memory [24]–[26] with better performance and efficient system. As a result, SMFP-LDs have attracted much attention for different applications. In order to extend its potential applications to photonics microwave, 5G mobile, biomedicine, defense, and others, microwave generation through feedback injection in SMFP-LD and external beam injection in dual-mode laser was recently carried out [28], [29], which are limited to only single beam injection, i.e., either feedback injection or external beam injection. However, the feedback injection system needs tunable filters, optical amplifier, and other corresponding optical devices for individual RF output. Hence, the cost, power consumption, and complexity of the system increase significantly. Also, the filter should be properly tuned every single time for generating microwave signals of different frequencies. In [29], the wavelengths of two modes in dual-mode laser lack wavelength tuning with a different wavelength differences. In addition, the scheme does not provide any insights on multiple beam injection, the possibility of generating multiband frequencies, and its effect on dual-mode beams.

In this paper, we propose a new method of generating individual and simultaneous multiple microwave, multiple millimeter waves, and terahertz signals together with frequency hopping of RF signals based on the injection of external beams with negative wavelength detuning into SMFP-LD. The main benefit of using SMFP-LD is the presence of self-injected dominant mode under the normal biasing condition; thus, only

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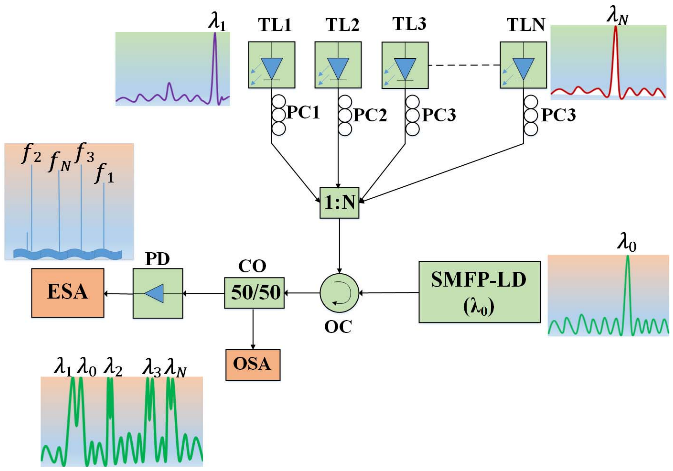

Fig. 1. Experimental setup of the proposed multiband frequency generator. ESA: electric spectrum analyzer; OSA: optical spectrum analyzer; PD: photo detector; OC: optical circulator; CO: coupler; PC: polarization controller; TL: tunable laser.

a single beam injection is enough for generating two different bands simultaneously through an optical beating. To achieve two different bands, an external beam is injected into any of the modes of SMFP-LD aside from the dominant mode. We also demonstrate switching between different regimes (millimeter to simultaneous millimeter and microwave and to microwave) by a simple mechanism of controlling injected beam power. This technique makes our approach simple, robust, versatile, and easy for frequency hopping. Furthermore, we investigate the feasibility of multiple beam injection in SMFP-LD with negative wavelength detuning to generate multiple frequencies (more than two) within the same and different bands. By injecting multiple beams, simultaneous generation of multiple bands of spectrum, i.e., Ku-, K-, Ka-, and V-bands, is observed, which can be further extended up to terahertz. The switching of generated signals with multiple beam injection is also demonstrated. The optical domain results from a few gigahertz to terahertz and electrical domain results from a few gigahertz up to 42.5 GHz are presented. These results verify the feasibility of using SMFP-LDs for multiple microwave, millimeter waves, and terahertz generation.

We analyze the effect of input beam power on the dominant mode, corresponding mode, and injected beam for generating different frequencies and switching among them with an injection of the single external beam into SMFP-LD, which is further extended to multiple beam injection. The wavelength and power stability of beating wavelengths, generation of harmonics, and linewidth of RF signals (up to 42.5 GHz) are also observed.

II. Experimental Setup

Fig. 1 shows the experimental setup of the proposed multiband frequency generator using an SMFP-LD. The SMFP-LD has a dominant self-locking single longitudinal mode with high SMSR. The SMFP-LD is obtained by eliminating the inclinations of 6°–8° of the coupling fiber present in conventional FP-LDs, thereby forming an external cavity between the laser diode and the fiber. The SMFP-LD consists of an FP-LD chip with a multiquantum well of 300 μm and an external cavity length of 4 mm. By varying the temperature, a mode-matching condition is achieved for both cavities. The refractive index of the active region changes with the change in temperature. As a result, there is a change in optical path length in the laser diode, providing the optimal mode-matching condition for single-mode oscillation. This single-mode oscillation can be tuned to another mode by varying operating temperature, which gives the tuning capability of the dominant mode wavelength to SMFP-LD. The self-locking mode of SMFP-LD is tunable over a wide range of wavelengths with a wavelength difference of about 10 nm [23]. SMFP-LD shows similar characteristics to those of multimode Fabry–Perot laser diode (MMFP-LD), including the mechanical stability, wavelength stability, power stability of laser diode, and output characteristics when subjected to optical injection of external beams. The only difference between SMFP-LD and MMFP-LD is that the former does not require an external probe beam for signal processing.

An LD driver (ILX Lightwave LDC-3724C) is used for biasing SMFP-LD, which has the functionality of changing the biasing current and the operating temperature. The operating temperature and biasing current define the wavelength and the power of the dominant mode of SMFP-LD. A four-channel tunable laser module, which is used for injecting external beams to the SMFP-LD, has features of varying wavelength and power that can be tuned from 1530 to 1560 nm and 5.5 to 16 dBm, respectively. The external beam can be injected with both positive and negative wavelength detuning to any of the modes, including the dominant mode of the SMFP-LD. Numerous studies have been carried out by injecting external beam with positive wavelength detuning, which gives the phenomenon of injection locking. While in injection locking, the mode is redshifted to the injected beam without or with suppression of the dominant mode. In contrast, while increasing the injected beam power with negative wavelength detuning, the corresponding side mode gains a sufficient amount of power before suppressing the dominant mode. As a result, microwave generation due to the optical beating of the corresponding side mode and injected beam is possible. Microwave generation by the optical beating of the corresponding mode and the external injected beam is not feasible with positive wavelength detuning. In our proposed multiband frequency generator scheme, four external beams (which can be further increased) are used: 1) to demonstrate the feasibility of multiple beam injection with negative wavelength detuning in SMFP-LD and 2) to generate a different bands of frequency individually or simultaneously. Attenuators, which are used at the output of laser source to reduce power, are not shown in Fig. 1.

At first, generation of millimeter wave, simultaneous microwave and millimeter wave, and microwave and the switching function is examined by using only single beam injection with negative wavelength detuning. Thereafter, multiple external beams are injected with the same and different wavelength detuning to their respective corresponding side modes. External beams can be injected into any of the modes of the SMFP-LD. Injecting external beam to farther modes of the SMFP-LD will result in higher wavelength difference between the dominant mode and the injected beam, generating RF signals of higher frequencies up to terahertz. The power of each beam is controlled and varied to analyze the effect of injected beam power on generation of RF signals and hopping from one regime to another. Polarization controllers (PCs) are used to control the polarization state of external beams to the SMFP-LD. An optical coupler with a power ratio of 1:N is used based on the number of inputs (N) injected. The output of the 1:N coupler is connected to one port of the circulator and passed through the SMFP-LD. The output from SMFP-LD with an injection of all external beams with TE polarization, which is obtained through a circulator, is divided into two branches by a 50:50 coupler. One output from the coupler is fed to an optical spectrum analyzer (OSA, Yokogawa AQ6370C) to observe optical spectra with a resolution of 0.02 nm and another to an electrical spectrum analyzer (ESA, Agilent E4447A) via a 50 GHz photodiode (PD, U^2t XPDV2120R) to measure the RF signal with a resolution bandwidth of 100 kHz.

III. Experimental Results

The SMFP-LD used in this experiment is biased with a biasing current of 24 mA and operating temperature of 26 °C. With these operating conditions, the SMFP-LD has a dominant mode at a wavelength of 1544.51 nm with SMSR of more than 34 dB. All injected beams in this experiment have a negative wavelength detuning unless stated, i.e., external beam is injected at the left side of the corresponding side mode, unlike in conventional injection locking. Injecting beam with negative wavelength detuning prevents mode shifting of the corresponding mode to the injected beam. Increasing the power of the injected beam with negative wavelength detuning, we observe three stages as follows.

1) The power of injected beam increases without suppressing the dominant mode of SMFP-LD, hence generation of RF signal by the optical beating of the dominant mode and injected beam is possible.
2) An increase in the power of injected beam, the corresponding side mode gains enough power without suppressing the dominant mode, as a result, simultaneous millimeter wave and microwave is possible.
3) Further increasing the power of the external beam, the dominant mode of SMFP-LD is suppressed and only microwave exists because of the optical beating of corresponding side mode and injected beam.

Hence, with the change in the power of the injected beam with negative wavelength detuning, we can switch (or hop) the generation from millimeter wave to simultaneous millimeter and microwave, to microwave and vice-versa. The external beam can be injected either in the dominant mode or any of the side modes of the SMFP-LD. The difference between injecting external beam in the dominant mode and corresponding side mode is that in the former, simultaneous millimeter wave and microwave is not feasible with only one injected beam as the external beam is injected into a dominant mode itself, which is one of the beating wavelengths. Hence, the only microwave is possible, which can be further extended to a higher frequency by changing wavelength detuning. Whereas in the latter, individual or simultaneous generation of millimeter wave and microwave is feasible with a single beam injection.

A. Simultaneous Millimeter and Microwave Generation and Switching With Single Beam Injection

At first, we injected single external beam to the first mode of SMFP-LD with negative wavelength detuning in order to analyze the effect of the injected beam for generating signals with different frequencies. The injected beam, 1545.52 nm, has a wavelength detuning of −0.13 nm with the first mode of SMFP-LD, 1545.65 nm. Since, the injected beam has negative wavelength detuning, on increasing external beam power, the injected beam gains sufficient power without shifting corresponding side mode to the injected beam. Whereas in positive wavelength detuning, the side mode shifts to the injected wavelength, causing either weak injection locking without suppressing the dominant mode or fully injection-locked with suppressing the dominant mode [30]. Hence, with negative wavelength detuning, it is possible to obtain millimeter wave by beating the injected beam 1545.52 nm and the dominant mode 1544.51 nm (wavelength difference of 1.01 nm), which corresponds to 126 GHz RF signal. In this case, the frequency of millimeter wave can be changed by varying the wavelength of injected beam. The side modes that present on a generation of millimeter wave can affect the performance of the RF signal. The minimum power difference between the desired wavelength and undesired wavelength (wavelength with maximum power, 1543.35 nm) is 31 dB, whereas the maximum power difference between desired wavelengths for the generation of a millimeter wave is 6.2 dB. The external beam can be injected into any side modes of SMFP-LD with any wavelength detuning for the generation of a millimeter wave.

Increasing the power of the external beam, the power of injected beam as well as corresponding side mode increases, as shown in Fig. 2(b). In Fig. 2(b), we observe three beams, the dominant mode of the SMFP-LD at the wavelength of 1544.51 nm, injected beam at the wavelength of 1545.52 nm, and corresponding side mode, which is the first mode in this case, at the wavelength of 1545.65 nm. Hence, it is possible for optical beating between the dominant mode and injected beam that provides millimeter wave and optical beating of injected beam and corresponding side mode generating microwave signal corresponding to the wavelength difference of −0.13 nm. The minimum power difference between desired and undesired wavelength, 1544.38 nm, is recorded as 23 dB whereas the maximum power difference between desired wavelengths is 6.8 dB. The undesired wavelength with the highest power in this case is 1544.38 nm, which is the harmonics generated due to the injection of external beam into the first mode. We can clearly see that the undesired wavelength has the same wavelength detuning of 0.13 nm with a dominant mode as that of the wavelength difference between the injected beam and the corresponding side mode. Even though harmonics are present, they do not affect the

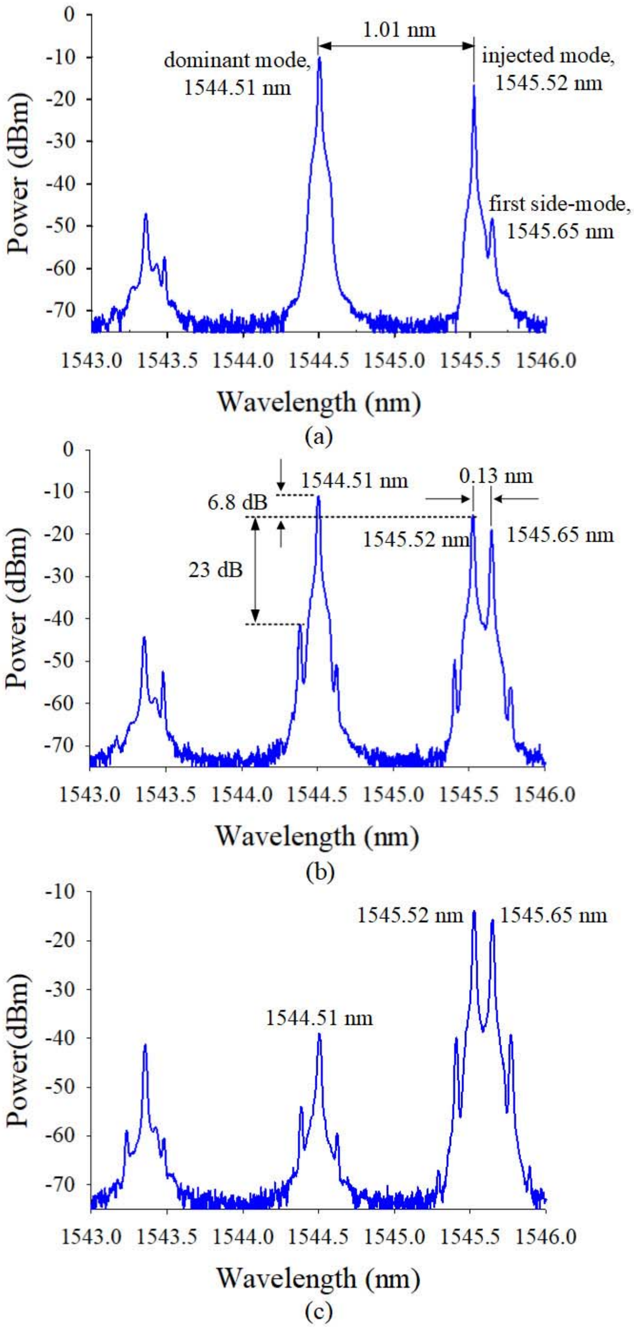

Fig. 2. Optical spectrum with single beam injection with negative wavelength detuning of −0.13 nm using different injected power that generates. (a) Millimeter wave. (b) Microwave and millimeter wave. (c) Microwave.

generation of the RF signal as the power ratio of desired wavelength to harmonics is higher than 23 dB. The respective minimum and maximum power difference between desired and undesired wavelength and desired wavelengths are little lower and higher, respectively, than that of the microwave generation. The power difference between desired wavelengths and undesired wavelengths can be improved by increasing the power of the injected beam. The measured value is not the optimum value of injected power, but the value recorded on the sharp transition from a millimeter wave to simultaneous millimeter wave and microwave. The performance can be improved by optimizing the power of injected beam. This shows the possibility of generating simultaneous microwave and millimeter wave with a single external beam injection. Changing wavelength detuning with the corresponding side mode, different frequencies of RF signals can be obtained whereas injecting the external beam to different side modes, abrupt shifts in frequency can be obtained. The changing of the injected beam from one mode to another mode provides the wavelength difference equivalent to a free spectral range (FSR) of laser diode. Injecting external beam to farther mode from the dominant mode generates millimeter wave with higher frequency. Whereas injecting external beam with positive wavelength detuning to the first-side mode, the corresponding mode (first mode) shifts to injected beam on increasing the power of the external beam. Hence, the simultaneous microwave and millimeter wave cannot be obtained, but with weak injection locking, millimeter wave is possible. Similarly, if the negative wavelength detuning is beyond half of FSR, which is 1.12 nm in this case, the injected beam with negative wavelength detuning to the first-side mode acts as a positive wavelength detuning to the dominant mode. As a result, the optical beating of first-side mode and injected beam is difficult to attain. Hence, in simultaneous microwave and millimeter wave generation, microwave range is limited to a frequency corresponding to half of the side mode. Also, a certain range of millimeter wave is not covered, which is equivalent to the wavelength difference of the dominant mode of SMFP-LD minus half of the FSR.

Further increasing the power of injected beam, the dominant mode of SMFP-LD is suppressed and only injected beam and corresponding side mode exists as shown in Fig. 2(c), which provides microwave signal. We can see that there are no changes in the wavelength of injected beam, dominant mode, and a corresponding side mode. It verifies our claim that optical beam can be injected with negative wavelength detuning without shifting the corresponding side mode to the injected beam unlike optical beam injection with positive wavelength detuning, where not only dominant mode is suppressed but also the corresponding mode shifts to the injected beam. Similar to other cases, the minimum power difference between desired and undesired wavelength is 24 dB and maximum power difference between desired wavelengths is 1.8 dB. The lesser power difference between desired wavelengths obtained in this case is due to the suppression of the dominant mode, as a result, the corresponding mode gains power abruptly on increasing injected beam power.

Fig. 2 and Table I verifies three cases: generation of (a) millimeter wave, (b) simultaneous millimeter wave and microwave, and (c) microwave, where the minimum power ratio of desired wavelengths and undesired wavelengths are more than 23 dB and the maximum power ratio between desired wavelengths are less than 7 dB. Also, the switching of generating RF signal is verified by changing the injected beam power.

In order to analyze the effect of the injected beam power for generating RF signal of different frequencies with negative wavelength detuning, we change the power of input injected beam from −15 to −2 dBm, as shown in Fig. 3. With the

TABLE I
POWER RATIO OF UNDESIRED SIGNALS TO DESIRED SIGNAL

	Millimeter wave	Microwave and Millimeter wave	Microwave
Desired wavelengths (nm)	1544.51 and 1545.52	1545.52, 1545.65 and 1544.51	1545.52, 1545.65
Generated frequency (GHz)	126	16.32, 126	16.32 GHz
Undesired wavelengths (nm) with highest power	1543.35	1544.38	1544.51
Minimum power ratio of desired wavelengths to others (dB)	31	23	24
Maximum power ratio between desired wavelength (dB)	6.2	6.8	1.8

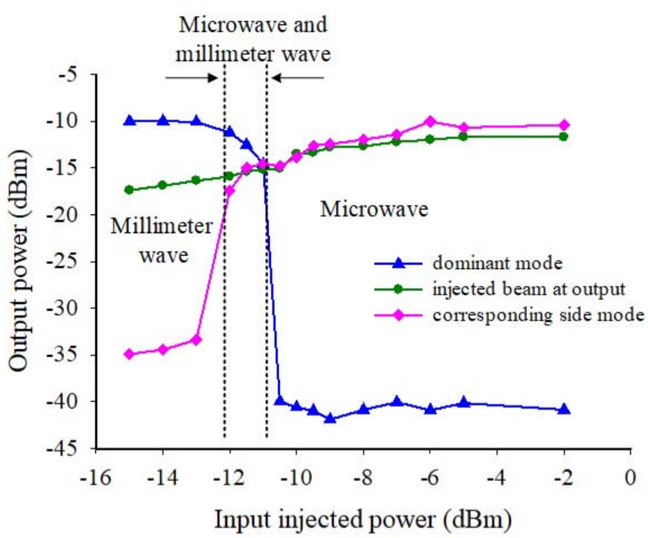

Fig. 3. Effect of input injected beam power on power of output dominant mode, injection mode and corresponding mode for generation of different band of frequencies for wavelength detuning of −0.13 nm.

change in injected beam power with negative wavelength detuning, the frequency of generated signal can be switched from one RF to another RF signal. Fig. 3 illustrates the input power requirement for generating and switching different band frequencies, the impact of input power on the dominant mode, corresponding side mode, and injected mode when the external beam is injected into the first-side mode with wavelength detuning of −0.13 nm. It is clear from Fig. 3 that millimeter wave is generated with a maximum power difference of 6.2 dB between desired wavelengths when the power of injected beam is −15.7 dBm. When the injected beam power is lowered than −15.7 dBm, the injected beam does not gain sufficient power required for an optical beating. This maximizes the power difference between required wavelengths for a millimeter wave generation. Whereas with an increase in the power of injected beam, the same RF band with the same frequency corresponding to the wavelength of 1.01 nm is generated till the input injected beam power reaches to −12 dBm. When the power of injected beam is increased to −12 dBm, the power of corresponding side mode increases abruptly from −34 to −16 dBm, as a result, simultaneous generation of millimeter wave and a microwave can be generated. We observe the dynamic power range of 1 dB (from −12 to −11 dBm) for generating simultaneous millimeter and microwave corresponding to wavelength detuning of 0.13 nm and wavelength difference of 1.01 nm (wavelength difference between the dominant mode at 1544.51 nm and injected beam at the wavelength of 1545.52 nm). The various frequencies of millimeter wave with a constant microwave can be obtained by injecting external beam to another side mode with the same wavelength detuning. Similarly, the microwave frequency can be changed by varying wavelength detuning with the injection of the optical beam into the same mode. The minimum and maximum wavelength detuning for this case is −0.02 and −0.56 nm (half of FSR). Changing wavelength detuning and the mode where the input beam is injected, different RF frequencies of millimeter wave and a microwave can be achieved; however, it has some constraints on RF frequencies due to the inherent mode spacing.

When the power of injected beam is beyond −11 dBm, the dominant mode is fully suppressed and only a microwave is generated by the optical beating of first-side mode and input-injected beam. In this case, the dominant mode is suppressed from −16 dBm to about −42 dBm providing a contrast ratio of about 26 dB, which can be increased by increasing the power of the injected beam. Further increasing the power of injected beam, we observe the generation of harmonics on both sides of the injected beam and corresponding beam with the same wavelength detuning of 0.13 nm.

We observe the minimum input dynamic power range of 1 dB for the generation of simultaneous microwave and millimeter as illustrated in Fig. 3. The dynamic input power range can be increased by biasing SMFP-LD with higher current because increasing the biasing current of SMFP-LD will strongly lase the dominant mode. Also, the input dynamic power range increases with increase in wavelength detuning because increasing wavelength detuning will reduce the effect of injected beam on the suppression of the dominant mode with a constant power of injected beam.

B. Multiple Signal Generation With Two Beams in Different Modes of SMFP-LD With Different Wavelength Detuning

In order to show the tunability of the dominant mode of SMFP-LD, the operating temperature is changed from to 26 °C to 23 °C and with biasing current of 24 mA. Under these conditions, SMFP-LD has a dominant mode at 1542.34 nm with −4.1 dBm beam power. The SMSR of

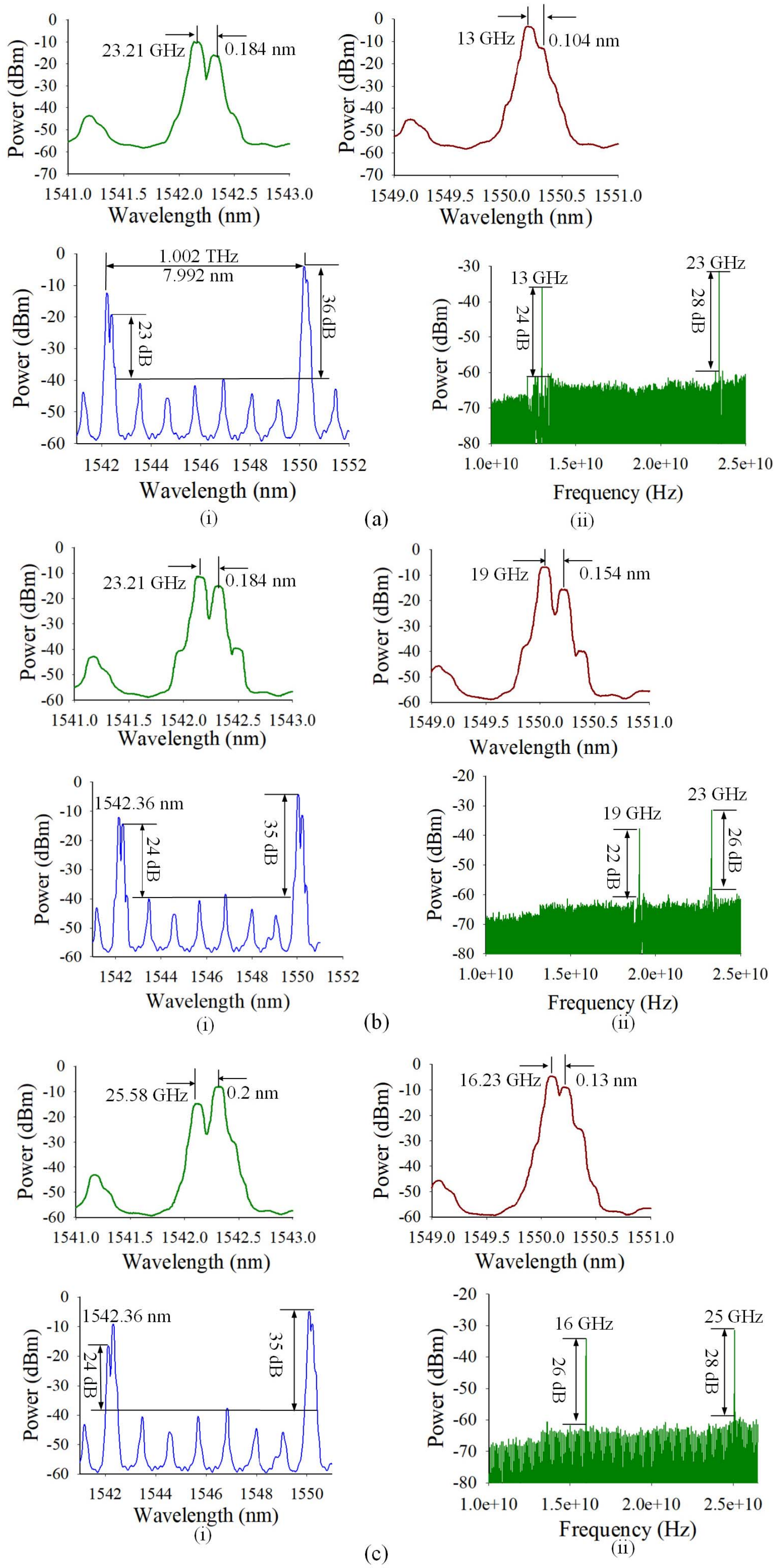

Fig. 4. Optical and electrical spectra with different wavelength detuning corresponding to the dominant mode and the seventh mode for generating two frequencies. (a) 0.184 and 0.104 nm corresponding to the frequency of 23 and 13 GHz. (b) 0.184 and 0.154 nm corresponding to the frequency of 23 and 19 GHz. (c) 0.2 and 0.13 nm corresponding to the frequency of 25 and 16 GHz.

SMFP-LD is recorded as 34.7 dB. Two beams are injected in SMFP-LD, among which one is injected at the dominant mode and another on the seventh mode of the SMFP-LD with wavelength detuning of −0.184 and −0.104 nm and injected power of −8.4 and −3.7 dBm, respectively. Under these conditions, injected beams on the dominant mode, seventh mode, and their corresponding side modes obtain sufficient power without suppressing the dominant mode. Hence, optical beating between injected beam and dominant mode and injected beam and corresponding mode are possible in PD, which gives the frequency of 23.21 and 13 GHz, respectively, as shown in Fig. 4(a). Fig. 4(a-i) shows the optical spectrum when two external beams are injected into SMFP-LD. Green spectrum and brown spectrum at the top of Fig. 4(a-i) are zoomed spectra with wavelength detuning of 0.184 nm to the dominant mode and 0.104 nm to the seventh mode of the SMFP-LD. Fig. 4(a-ii) shows electrical domain result obtained through the beating of the external beam and their corresponding modes of the SMFP-LD, which corresponds to the frequency of 13 and 23 GHz. The minimum ratio of RF signal power to other frequencies is more than 25 dB in both cases. The result shows multiple beams can be injected into any of the modes either in the dominant mode or any of the side modes with different wavelength detuning for generating different band of frequencies. The power required by injected beam increases with an increase in negative wavelength detuning for generating microwave and millimeter wave. Also, the power requirement of the injected beam for suppressing the dominant mode and the power gained by corresponding side mode depends on the power of corresponding side mode without any beam injection. In Fig. 4(b) and (c), external beams are injected in the dominant mode and side mode with different wavelength detuning, keeping one wavelength detuning constant and changing the other. Later on, we change wavelength detuning of both beams from Fig. 4(a). Results under this condition justify that changes on one wavelength detuning do not effect on the other. In Fig. 4(b), wavelength detuning to the seventh mode is changed whereas in Fig. 4(c), the wavelength detuning to both dominant mode and the seventh mode is changed as compared to Fig. 4(a), which gives a different combination of frequencies; 23 and 19 GHz and 25 and 16 GHz. The electric domain results are shown in Fig. 4(b-ii) and (c-ii) for the same. In all these cases, the power ratio of desired RF signal to other RF frequencies is more than 24 dB. Besides, the optical beating of the dominant mode and injected beam on the seventh-side mode can generate RF signals in terahertz range, which is supported by the optical spectrum result in Fig. 4. Injecting beam farther to the dominant mode will generate higher RF frequencies than injecting beam nearer to the dominant mode. The electrical domain result of higher frequency generated due to the optical beating of dominant mode and injected beam on the seventh mode is not presented due to the limitation of the operating range of PD and ESA. However, the feasibility can be claimed based on optical beating wavelength stability, power stability, and linewidth presented in the later sections, and research work performed by other research groups. With these optical and electrical domain results, we are convinced that multiband frequency generator can be obtained through SMFP-LD, which covers X-band, Ku-band, K-band, and can also be further extended to frequency spectrum to terahertz range.

C. Multi-Input Injection on SMFP-LD for Multiband RF Signal Generation and Switching

Further SMFP-LD is analyzed for three and four injected beams with negative wavelength detuning at different side modes to show multi-input capability for generating simultaneous multiple RF signals of the same and different frequency bands. The number of injected beam can be increased to the number of modes of the SMFP-LD. Increasing number of input beam will effect on the dominant mode power. The maximum number of input, up to eight, with positive wavelength detuning for multi-injection has been reported [31]; however, it has not been implemented for generating an RF signal. Also, the switching from one band of frequency to another can be achieved similarly as illustrated in Figs. 2 and 3. Three beams are injected into the first, second, and fourth modes of SMFP-LD with the same wavelength detuning whereas four input beams are injected into the first- to fourth-side modes with different wavelength detuning as illustrated in Fig. 5. As in single beam injection, by varying the power of input beams, millimeter wave, simultaneous millimeter and microwave, and a microwave can be obtained in the multi-input injection. The generated frequency of microwave corresponds to wavelength detuning of injected beam to the side mode, whereas that of millimeter wave corresponds to the wavelength difference of the dominant mode and input injected beams as well as the wavelength difference between the injected beams. Fig. 5(a) shows the generation of millimeter wave by beating the dominant mode and individual injected input beams. The simultaneous generation of millimeter and microwave is illustrated in Fig. 5(b) with the same wavelength detuning of −0.13 nm. Further increasing the power of injected beam, only microwave is generated by suppressing the dominant mode of SMFP-LD, as shown in Fig. 5(c). While generating RF signals of the same frequency by beating different optical beams with the same wavelength detuning, as shown in Fig. 5(c), coherency should be considered, which can vary the linewidth of the generated signal and phase noise. Since all injected beams in a single SMFP-LD maintain the same polarization, the performance on output coherency may not be significant. Further analysis on coherency with multiple injected beams should be interesting, but is beyond the scope of this research work. The wavelength detuning of injected beams can be different with individual beam injected into different modes, which provide different frequencies of microwave belonging to different bands of the IEEE Radar Band Designations [32]. In Fig. 5(d), four input beams are injected with different wavelength detuning of −0.13, −0.19, −0.31, and −0.34 nm with the first to fourth mode that generates the frequency of 17.58 (Ku-band), 23.82 (K-band), 38.76 (Ka-band), and 42.5 GHz (V-band), simultaneously. The wavelength detuning and the mode of the injected beam can be varied to generate other bands, C-band, X-band, and terahertz signals. The optical spectrum with four injected beams with different wavelength detuning is shown

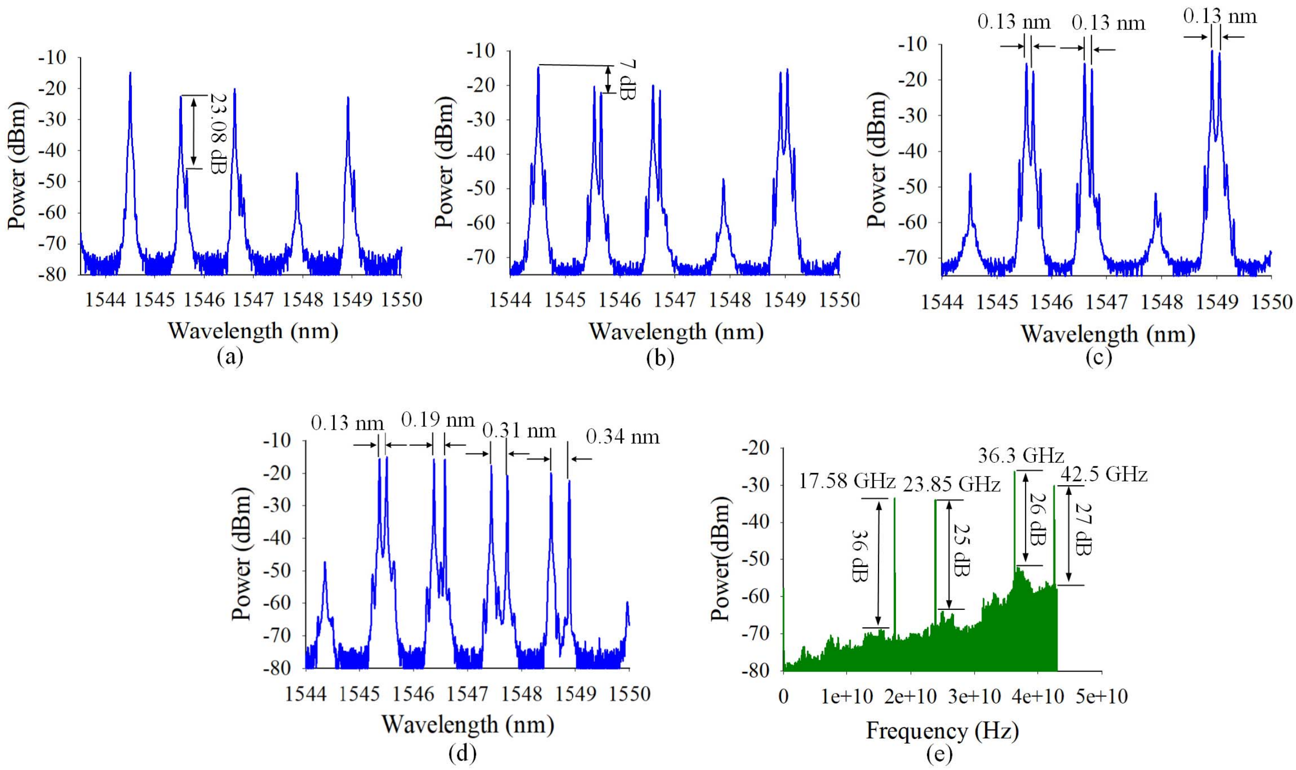

Fig. 5. Output results. (a) Millimeter wave with three injected beam with constant wavelength detuning. (b) Millimeter and micrometer. (c) Microwave with the same wavelength detuning of −0.13 nm. (d) Microwave generation with four injected beams with different wavelength detuning. (e) Electrical output of generated signal, which corresponds to the optical output of (d).

in Fig. 5(d). From Fig. 5(a), the minimum power ratio of the desired signal to the power of undesired signal in the optical domain is measured to be 23.08 dB whereas the maximum power difference between the desired wavelengths is about 7 dB, as shown in Fig. 5(b). In all other cases, the power ratio between desired to undesired and the power ratio among desired wavelengths is measured above 23 dB and below 7 dB, respectively. Fig. 5(e) shows the electrical domain result corresponding to the optical domain result of Fig. 5(d). In optical domain result, the minimum power ratio between desired wavelength and undesired wavelength is more than 30 dB whereas the maximum power difference between the desired wavelengths is less than 2 dB. The minimum and maximum RF signal to noise is about 25 dB (for RF frequency of 23.85 GHz) and 36 dB (for RF frequency of 17.58 GHz), respectively, as shown in Fig. 5(e).

In the proposed method, each beam can be controlled separately without affecting other injected beams. As a result, power and wavelength of the individual injected beam for generating millimeter wave, simultaneous microwave and millimeter wave, and microwave are independent of the power and wavelength of other injected beams. This feature gives the flexibility on the usage of each injected beam for generating only microwave by beating injected beam and its corresponding side modes or only millimeter wave by beating injected beam and the dominant mode of the SMFP-LD or any of other injected beams.

Table II shows the power of different beams for generating microwave and millimeter wave, and microwave with the same wavelength detuning injected in different modes. The small difference in the suppression and gain of different modes may be due to the mode power of SMFP-LD before injection of the external beam. The independency of side mode on output performance is achieved because external beams are injected with negative wavelength detuning. In negative wavelength detuning, the wavelength of side mode does not shift to injected beam and the side mode power increases before the suppression of the dominant mode. On the contrary, injecting beam with positive wavelength detuning shifts the side mode to injected beam, suppressing the dominant mode. Also, the power required for suppression of the dominant mode increases with injecting external beam to farther mode than injecting external beam to nearer mode. It is clear from Table II, the maximum power difference between required wavelengths for generating microwave and millimeter wave is below 2 and 3 dB, whereas the power ratio of the dominant mode to required wavelengths for generating microwave is above 35 dB. The power of injected beam is made constant as −9.11 dBm for the generation of millimeter and microwave and −3.65 dBm for the generation of microwave.

D. Power Stability, Beating Wavelength Stability, and Linewidth Measurements

The input power requirement for generating microwave and high frequencies RF signal, stability of beating wavelengths, their power variation, and linewidth of generated RF signals are illustrated in Figs. 6 and 7. Fig. 6(a) shows the power requirement for generating millimeter wave, simultaneous millimeter and microwave, and microwave corresponding to

TABLE II
OUTPUT POWER OF THE DOMINANT MODE, INJECTED MODE, AND CORRESPONDING MODE FOR GENERATING DIFFERENT BAND SIGNALS

	Millimeter and microwave with input power -9.11 dBm			Microwave with input power -3.65 dBm		
Power (dBm) / mode	Dominant mode (dBm)	Injected mode (dBm)	Corresponding side mode (dBm)	Dominant mode (dBm)	Injected mode (dBm)	Corresponding side mode (dBm)
1st mode	-13.32	-16.82	-17.44	-49.97	-13.09	-13.91
2nd mode	-13.12	-16.01	-16.84	-51.66	-15.7	-15.14
3rd mode	-12.88	-15.21	-15.29	-45.62	-12.21	-14.29
4th mode	-13.12	-13.28	-14.11	-48.28	-13.11	-13.67

the wavelength detuning of −0.19 nm, which is injected into the first-side mode. It is clear from Figs. 6(a) and 3 that higher the wavelength detuning higher the power requirement of input injected beam for the generation of millimeter wave, simultaneous millimeter and microwave, and microwave. The requirement of higher input injected power for higher wavelength detuning while generating microwave with negative wavelength detuning holds the same to that of injecting beam with positive wavelength detuning [33], [34]. The desired beams in Fig. 6(a) are the dominant mode (purple line), first-side mode (black line), and injected beam (dark green line). Others are side modes of SMFP-LD, except for pink and red lines in Fig. 6(a). New wavelengths (red and pink lines) are the harmonics of beating wavelengths. The wavelength difference between newly generated wavelengths is twice the wavelength detuning of injected beam and corresponding side mode. It is also seen that the beating wavelengths remain constant irrespective of the power of the input injected beam. Fig. 6(b) and (c) shows the power variation and the wavelength variation of beating wavelengths for RF generation, which we observed for 1 hour with the time interval of every 5 min. The same colored lines denote beating wavelengths of optical beams required for generating RF signals. Dotted lines represent the side mode or dominant mode and solid lines represent injected beams. The maximum variation in the power of individual beating wavelengths is about 0.2 dB measured over 1 hour time period, whereas the maximum power difference between beating wavelength required for generating RF signal is 6.8 dB for the wavelength difference of 7.99 nm, which corresponds to the RF frequency of about 1 THz. Fig. 6(c) illustrates wavelength variation of beating wavelengths required to generate RF signal and are constant within the resolution of OSA, 0.02 nm, which we observed for 1 hour.

Fig. 7 illustrates linewidth and RF power spectra of the generated RF signal. The measured linewidth for 42.5 GHz signal is less than 300 KHz. The linewidth of the generated RF signal increases with increase in frequency, which shows that the linewidth of RF signal not only depend on the linewidth of optical beams used for optical beating, but also to numerous other factors, which are further discussed on other literatures [35], [36].

IV. DISCUSSION

Figs. 2–7 show the feasibility of generating and switching of multiple RF signals with different frequencies simultaneously, which ranges from a few gigahertz to terahertz using single SMFP-LD. The switching of generated RF signal is obtained through the power variation of the input injected beam. With the change in injected beam power, hopping from the generation of millimeter wave to simultaneous millimeter and microwave, and to microwave and vice versa is obtained by a simple mechanism of changing injected beam power. It is noted that all injected beams in the experiment are with negative wavelength detuning. The negative wavelength detuning is chosen because it prevents injection locking and does not shift corresponding side mode to the injected beam. However, a negligible small wavelength shift occurs when injected power is very high. Since wavelength shifting is prevented by negative wavelength detuning, an increase in power of the injected beam increases the power of the corresponding side mode to the sufficient level to generate simultaneous millimeter wave and microwave signal. In simultaneous millimeter and microwave generation, microwave range is limited to the frequency corresponding to half of the side mode whereas the millimeter wave is limited to the frequency corresponding to the wavelength difference of injected beams and the dominant mode of the SMFP-LD minus the half of the FSR. But there is no any constraint on generating single RF signal whether the RF signal is microwave or millimeter wave. From Figs. 2–6, we can see that the corresponding side mode gain sufficient power before the power of the dominant mode drops significantly. We also observed that the power difference of beating wavelengths required for millimeter wave is larger than that of the microwave. Moreover, injected beams in SMFP-LDs can have different wavelength detuning to corresponding side modes irrespective to other injected beam, as a result, multiband frequency can be generated as illustrated in Fig. 5(d). On the contrary, if optical beams are injected with positive wavelength detuning, which is often used in the state-of-the art techniques and many literatures, the wavelength of corresponding side mode shifts to injected beam on increasing the power and injection locking occurs with suppression of the dominant mode. This eliminates the feasibility of simultaneous millimeter wave and microwave generation with positive wavelength detuning using a single beam injection.

Figs. 2–5 verify that the injected beam can be either injected into the dominant mode or any of the side modes. If the external beam is injected into the dominant mode, only one RF signal can be generated whose frequency can range from microwave to terahertz signals. Fig. 5 illustrates the feasibility

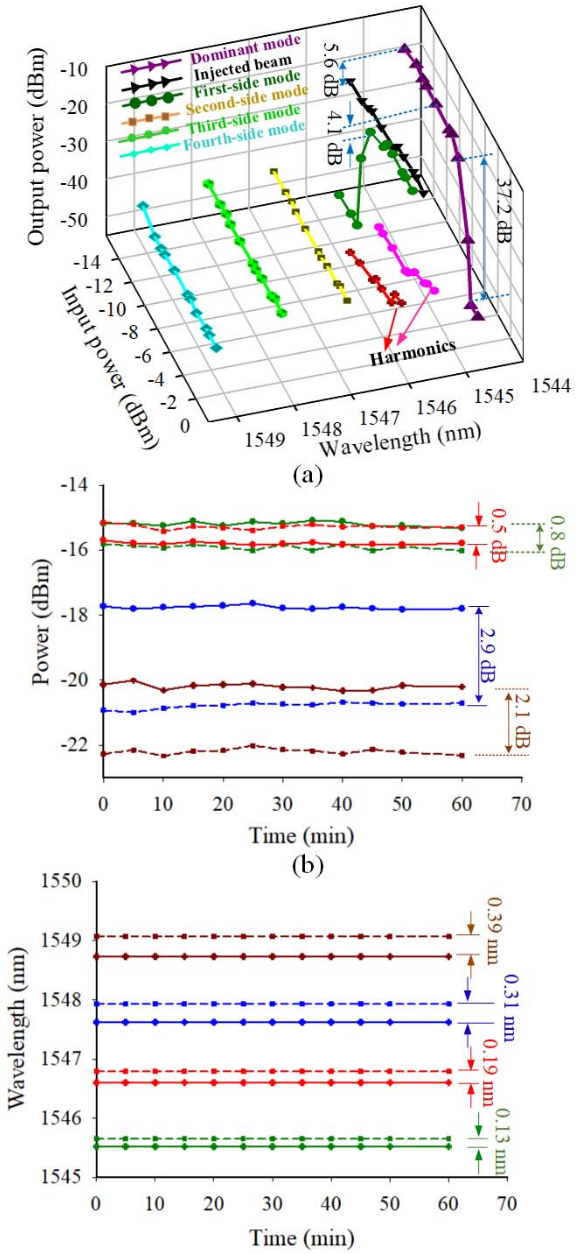

Fig. 6. Analysis of optical beating wavelengths. (a) Power variation of the dominant mode, injected beam, corresponding side mode and other side modes with constant wavelength detuning of −0.19 nm. (b) Power variation of beating wavelength over 1 hour. (c) Wavelength variation of beating wavelengths over 1 hour. The dotted line indicates the corresponding side mode or the dominant mode, whereas solid line indicates injected beams. The same color indicates the beating wavelength for generating microwave and millimeter wave.

of multiple numbers of injected beams with the same and different wavelength detuning in SMFP-LD for generating frequencies from a few gigahertz to terahertz with a different band of frequencies. Since injection with negative wavelength detuning does not shift the wavelength of corresponding mode to the wavelength of the injected beam, we believe that the number of inputs can be further increased to more than four based on the fact that previous researchers have successfully analyzed and demonstrated injection locking with eight inputs beams in FP-LD [31]. It would be interesting to investigate the potential to generate more than four different bands

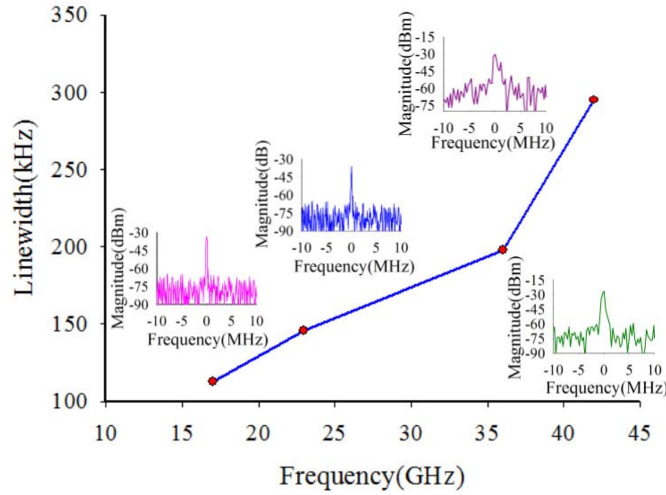

Fig. 7. Linewidth and power spectra of generated multiband (Ku-, K-, Ka-, and V-band) RF signal.

using negative wavelength detuning and analyze the effect of increasing injected beam on power requirement, linewidth, and phase noise. Moreover, output signals are controlled individually by the power of each injected beam making it simple, stable, and less dependent with other beams. With the increase in a number of injected beams, each individual beam can contribute for generating multiple millimeter waves along with multiple microwave generation. The wavelength variation, power stability of beating wavelength, and linewidth of RF signal are presented in Figs. 6 and 7. From the observed results of stability of beating wavelength, power and linewidth, we can expect less phase variance and phase noise in the electrical domain. However, further investigation is needed for the claim, which is beyond the scope of this paper, would be interesting to further explore theoretically and experimentally in the future work.

V. Conclusion

In this paper, we proposed and demonstrated a novel approach to generate simultaneous multiband frequency and frequency switching from one band to another. The proposed method is simple and stable as it has few control parameters such as the power of injected beams, wavelength detuning, and numbers of injected beams. The proposed method is also robust and strictly avoids fault propagation from one output to another because each input beam can be controlled individually while generating multiple signals of the same or different frequencies that fall on C-band to V-band and higher up to terahertz. Unlike in many state-of-the-art techniques, we propose negative wavelength detuning instead of positive detuning. In negative wavelength detuning, shifting of side mode does not occur and gives a better wavelength stability, which, in turn, can give better RF frequency stability. On the contrary, positive detuning leads to injection locking with corresponding side mode shifting to the injected beam. The effect of the power of injected beam to the dominant mode, corresponding side mode, and injected beam is analyzed. We found that varying the power of injected beam, the RF frequency generation can be switched from millimeter wave to simultaneous millimeter and microwave, to microwave, and vice-versa. The feasibility of injecting multiple beams with negative wavelength detuning for generating a different band of frequencies is also verified with multiple input beams injection with the same and different wavelength detuning. The stability of beating wavelength, power, and RF linewidth are also presented to predict the stability of generated frequencies with multiple beam injection using single SMFP-LD.

This paper is the first time that uses the injection of a multiple numbers of beams in SMFP-LD with negative wavelength detuning for generating simultaneous RF signals of different bands. Also, frequency hopping between generated different bands of frequencies is shown with single and multiple beam injection by varying the power of injected beams. Since we use only one SMFP-LD and injected power is the only parameter to control for frequency hopping, the operation, and configuration of the proposed scheme is simple. As multiband frequencies are generated within a single SMFP-LD, the generated signal can be used for optical wireless networks, spectroscopy, and variable oscillators. Also, the proposed techniques have the feasibility to switch from one frequency to another and from one band to another within the same physical configuration. This can be used for random signal channels and has strong potential in a secure military communication, detecting different objects for radar, and many others.

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