Microwave Frequency Generation, Switching, and Controlling Using Single-Mode FP-LDs

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***Abstract*—RF signal generation, switching, and reconfiguring are essential and important features for the rapidly developing microwave system, which are usually implemented using independent components or subsystems. In this paper, we propose and demonstrate an optical method to generate and switch the RF frequency at the stage of generation based on control input state using external cavity based single mode Fabry–Pérot laser diode. The RF frequency generation, switching, and controlling are based on the principle of injection locking with negative and positive wavelength detuning. In the proposed scheme, a single external beam is simultaneously used to control RF switching as well as to generate RF signal through optical heterodyning of injection locked beams. This eliminates the necessity of two separate external beams to switch and generate RF signal. Based on the logic state of the input control beam, the frequency of the generated RF signal can be changed to another RF frequency within a group of predefined RF bands. In a proof-of-concept experiment, a 2-Gbps, 16-bit nonreturn-to-zero control signal is applied to switch the frequency of the generated RF signal. We obtain the minimum signal to noise power ratio of more than 23 dB, the maximum linewidth of 165 kHz, and rising and falling times of less than 40 ps associated with the RF switching. The tunable range, RF frequency, and RF power variation of the generated RF signals are also observed. Moreover, using random control signals, random sequences of RF frequencies can be generated using the same experimental and hardware setup. Such reconfigurability and flexibility of our system to generate several random RF signals from the same framework enables application of the proposed method in several fields such as secure communication, encryption, and military applications.**

***Index Terms*—Injection locking, microwave photonics, single mode Fabry-Pérot laser diode, switching, wavelength detuning.**

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I. Introduction

Microwave photonics has shown immense potential applications in 5G mobile communication, radars, secure communication, satellite communication, and instrumentation [1]–[6], of which re-configurability and switching characteristics are among the most desired features [7]–[9]. Compared to its electronics counterpart, photonic generation, switching, and controlling of RF signals overcomes the issues of electromagnetic interference, limited bandwidth and long switching time [1], [2]. Optical fiber lasers [10], semiconductor lasers [11], and photonic crystals [12] have been used as integratable components of photonics microwave system that includes signal generation and switching functions. Amongst these, semiconductor lasers such as VCSELs [13], SOAs [14], and Fabry-Pérot laser diodes (FP-LDs) [15] have shown theirs significant presence on optical signal processing and microwave generation for a long time [16], [17]. Recently, single-mode Fabry-Pérot laser diodes (SMFP-LDs) [18] are also used for microwave generation using feedback techniques, external beam injection and dual mode lasers. Different techniques such as homodyne [19], heterodyne optical phase-locked loop [20], optical frequency combs [21], side-band locking [22], orbital angular momentum [23] and feedback injection locking [24] are used for the microwave generation with their corresponding pros and cons. However, there are limited works and literatures that investigate the re-configurability and switching of RF signals at the stage of generation. Recently feedback injection locking and injection locking in SMFP-LDs have been used for generating microwave signals [25], [26]. The advantages of its inherent characteristics of self-injected dominant mode can be extended to RF switching and controlling. On top of the self-injected dominant mode, SMFP-LD also provides high side modes suppression ratio, less complexity, and does not require additional probe beam for signal processing unlike in other semiconductor lasers [27].

In this paper, we demonstrate a scheme to switch and control the RF frequency at the stage of generation using external cavity based single mode Fabry-Pérot laser diode (SMFP-LD). The proposed scheme is based on the injection locking with negative and positive wavelength detuning. The scheme consists of two units: control and the generation unit. Among the two, the control unit is a simple switch, which generates the control output signal based on the input bit of the control unit and works on injection locking with positive wavelength detuning, whereas, the generation unit works on the injection locking with negative wavelength detuning. We use external beam injection locking technique instead of feedback locking for generation of RF signal to overcome the necessity of filters, amplifiers, couplers, and other associated components. Moreover, our innovative framework needs only a single external beam for generation and switching, and provides fast switching of RF signals based on control beam state. A single external injected beam is used as the control signal for switching function as well as one of the beating signals required for RF generation through an optical beating in the photodiode. We analyze both weak and strong injection locking for switching the RF generation. The external injected beam, which controls the switching of RF generation with different frequency, is modulated with 2-Gbps, 16-bit non-return-to-zero (NRZ) data. Based on the control signal i.e., logic '1' or logic '0', the frequency of generated RF output switches from one frequency to another. The optical spectrum results of the proposed scheme of switching and controlling the frequency of RF generation are presented. Electric domain results (from ESA and RTO) are also presented within the range of 42.5 GHz. The linewidth, stability of beating wavelengths, frequency and power of the generated RF frequency are observed. Oscilloscope traces of output signals with rising and falling times of about 40 ps are observed while switching the frequency of RF signal generation from one frequency/band to another.

II. Basic Operating Principle

The basic principle of the proposed scheme of switching and controlling the RF frequency at the stage of microwave generation using SMFP-LD is the injection locking. The proposed scheme consists of two units: (1) control unit that consists of SMFP-LD1 and (2) RF generation unit that consists of SMFP-LD2, which are shown in Fig. 1(a). The control unit which provides a control output signal for switching the frequency of RF generation is based on the injection locking phenomena with positive wavelength detuning and acts as a simple switch [27] whereas the RF signal generating unit is based on the injection locking with negative wavelength detuning [26]. The beams that are used for generating RF signal are injection locked to one of the side modes of SMFP-LD2. The external beam, λ_c, which is injected to SMFP-LD1 decides the beam to be injected in SMFP-LD2 for the generation of RF signal. Depending on the presence or the absence of λ_c, the beam injected to SMFP-LD2 is either λ_c or the dominant mode of SMFP-LD1, λ_1, respectively. The outputs of SMFP-LD1, whether it is an external beam or a dominant mode of SMFP-LD1, or both in the case of weak injection locking, are managed in such a way that the injected beams have negative wavelength detuning to the corresponding modes of SMFP-LD2. Fig. 1(b) illustrates the basic operating principle of the proposed scheme of switching the RF generation from one RF to another. SMFP-LD1 and SMFP-LD2 have self-injected dominant mode at the wavelength of λ_1 and λ_2, respectively as shown in Fig. 1(b)–(i) and 1(b)–(ii). When λ_c is not present, the dominant mode of SMFP-LD1, λ_1, is injected to the 1st side mode (right to dominant mode) of SMFP-LD2 with negative wavelength detuning as shown in Fig. 1(b)–(iii). Since, λ_1 is injected with negative wavelength

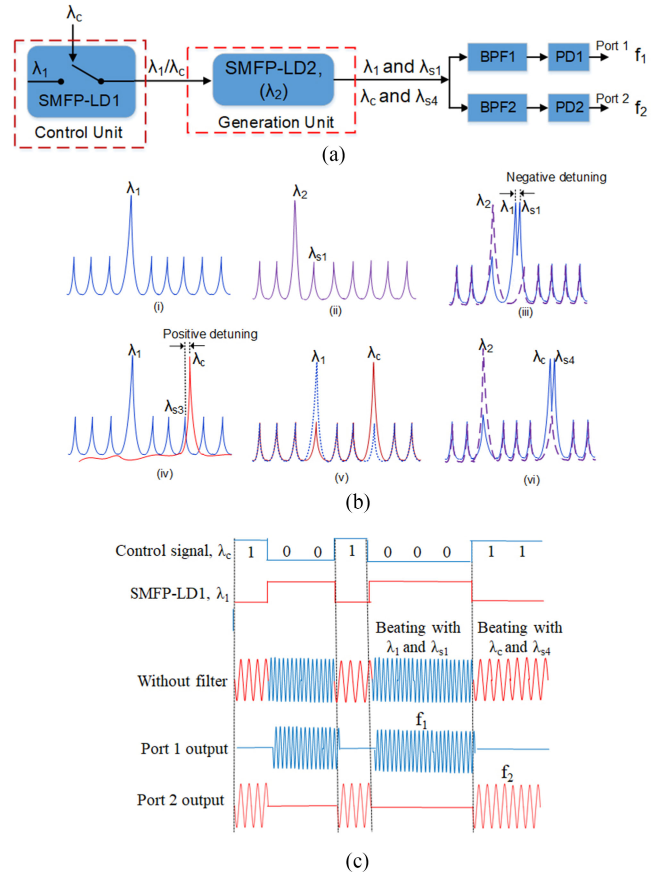

Fig. 1. Basic principle of switching of the RF generation: (a) block diagram, (b) schematic illustration of operating principle through schematic of spectrum diagram, and (c) schematic illustration of switching of the RF generation.

detuning, the modes of SMFP-LD2 are not red-shifted and the corresponding side mode get sufficient power required for optical beating to generate the RF signal of frequency f_1 (equivalent to the wavelength difference of $\Delta\lambda = |\lambda_1 - \lambda_{s1}|$) at the output port 1.

In contrast, when λ_c is present i.e., the control signal is injected to SMFP-LD1 with positive wavelength detuning to 3rd side mode (right of dominant mode) as shown in Fig. 1(b)–(iv), the dominant mode of SMFP-LD1 is suppressed with sufficient contrast ratio, illustrated in Fig. 1(b)–(v). As a result, only the control signal, λ_c, is injected to SMFP-LD2. It is noted that λ_c has negative wavelength detuning to the 4th side mode of SMFP-LD2 as shown in Fig. 1(b)–(vi). In this case, the RF signal of frequency f_2 (equivalent to the wavelength difference of $\Delta\lambda = |\lambda_c - \lambda_{s4}|$) can be obtained through output port 2. Hence, based on the absence or presence of control beam λ_c, switching of RF generation from f_1 to f_2 can be obtained. The output can be obtained from the single port output by removing the band pass filters (BPFs) and using a single photodiode (PD) at the output of SMFP-LD2. In single output case, based on the control input the switching between RF signals of frequencies f_1 and f_2 can be obtained as shown in the Fig. 1(c)–without filter. It is noted that the injected beams are injection locked on corresponding SMFP-LD regardless of the positive or negative wavelength detuning.

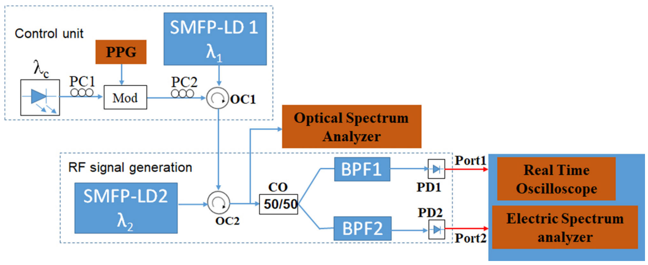

Fig. 2. Experimental setup of the proposed scheme of switching of RF signal generation.

By varying the power of control output beam that is injection locked with negative wavelength detuning to SMFP-LD2, simultaneous millimeter and microwave signals with frequencies equivalent to the wavelength difference of $\Delta\lambda = |\lambda_c - \lambda_{s4}|$), $\Delta\lambda_1 = |\lambda_2 - \lambda_c|$) and $\Delta\lambda_2 = |\lambda_c - \lambda_{s4}|$) can be generated which are discussed briefly on latter section. Also, the external beam and the self-injected dominant mode can be tuned to provide different wavelength detuning by varying the wavelength of the control beam and tuning the temperature and biasing current for SMFP-LDs. The only constraint on the wavelength selection is to maintain the positive wavelength detuning of the control signal to the modes of SMFP-LD1 and negative wavelength detuning of injected beams to the modes of SMFP-LD2. The change in the wavelengths of the control signal and the dominant mode of SMFP-LD1 will change the wavelength detuning of injected beam to SMFP-LD2 and consequently, the frequencies of RF signals at the output change as well. The control beam, λ_c, can be modulated with a random bit sequence as shown in Fig. 1(c); as a result, RF signal within a random sequence of predefined frequencies can be generated at the output. It is seen from Fig. 1(c), with a change in the states of the control beam (presence or absence of the control beam), the frequency of generated RF signal changes. Based on the requirement, the individual frequency can be outputted from the separate ports by using separate BPFs and PDs for individual frequency as shown in Fig. 1(c). Furthermore, the injected beam to SMFP-LD2 can be used for switching the generation of simultaneous multiple RF signals of different bands by varying the power of injected beams to SMFP-LD2 with the same configuration, which is illustrated in latter sections. This is possible due to the weak injection locking and negative wavelength detuning injection to SMFP-LD2.

III. Experimental Setup and Results

The experiment setup of the proposed scheme of switching and controlling the frequency of RF signal using SMFP-LDs at the stage of RF generation is shown in Fig. 2. The proposed scheme has two SMFP-LDs as main active components. SMFP-LDs are modified from commercially available MMFP-LDs with external cavity. In construction, SMFP-LDs have an external cavity of 4 mm that is formed by cutting the inclination of coupling fiber present on MMFP-LDs. MMFP-LDs and SMFP-LDs have similar characteristics and operating principle except for the latter, it has the self-injected dominant mode and hence does not require any external probe beam for signal processing. Therefore, SMFP-LDs have benefits of simple configuration, low cost, and low power consumption. Due to these advantages compared to MMFP-LD and other semiconductor laser diodes, we focused on SMFP-LDs for the proposed scheme. In order to operate SMFP-LDs, laser diode (LD) drivers (ILX Light wave LDC-3724C) are used. Laser diode drivers have the facility of changing the biasing current and temperature, which determine the self-injected dominant mode of SMFP-LD. By varying the temperature and the biasing current, the dominant mode of SMFP-LD can be tuned within a wavelength range of 10 nm. A tunable laser source (TLS), Agilent N77714A, is used for the control signal that can vary the wavelength and power of the beam from 1530 to 1560 nm, and 5.5 to 16 dBm, respectively. The control signal is modulated by Non-Return-to-Zero (NRZ) signal from pulse pattern generator (PPG) with the data rate of 2 Gbps. Polarization controllers (PCs), PC1 is used to minimize the loss in Mach-Zehnder modulator whereas PC2 is used to maintain the TE mode of the beam injected to SMFP-LD since injection locking works on TE mode. The output from the SMFP-LD1 is fed to SMFP-LD2 through optical circulator, OC1. The output from SMFP-LD2 is passed through OC2 and divided by 50/50 optical coupler, CO. Optical filters are placed on both ports in order to filter out only necessary signal at the outputs and passed through 50-GHz photodiode (PD, U2t XPDV2120R). Optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm is used before CO to analyze the entire optical signal. Electric domain results are measured by electrical spectrum analyzer (ESA, Agilent E4447A with a maximum measurement of 42.5 GHz) with a resolution bandwidth of 100 kHz and real-time oscilloscope (Agilent DSO-X-92504A with a maximum measurement range of 33 GHz). The electric domain result can be measured before the CO with the addition of PD in order to observe the switching or transition from one RF signal to another.

The proposed scheme consists of two SMFP-LDs among which, one (SMFP-LD1) is used for the control unit, i.e., controlling the beams that are to be injected into another SMFP-LD (SMFP-LD2) for optical beating in RF generation unit. Depending upon the output of control unit and the modes, where the control output beam is injected in SMFP-LD2, either single or multiple RF signals of same or different frequencies and IEEE Radar Bands can be generated. The switching between generations of the RF signal is determined by the presence or absence of the control input whereas the frequency of the generated RF signal is determined by the wavelength difference of the beating signals. SMFP-LD1 and SMFP-LD2 are biased with the biasing current of 19.2 mA and 22.8 mA, and operating temperature of 21 °C and 25.3 °C, respectively. Under these operating conditions, SMFP-LD1 and SMFP-LD2 have the self-injected dominant mode at the wavelength of 1543.74 nm (λ_1) and 1547.55 nm (λ_2). Both SMFP-LDs have the same free spectral range (FSR) of 1.12 nm. SMFP-LD1 is biased in such a way that the dominant mode of SMFP-LD1, λ_1, provides negative wavelength detuning with any of the modes of SMFP-LD2. Similarly, control beam, λ_c, is arranged in such a

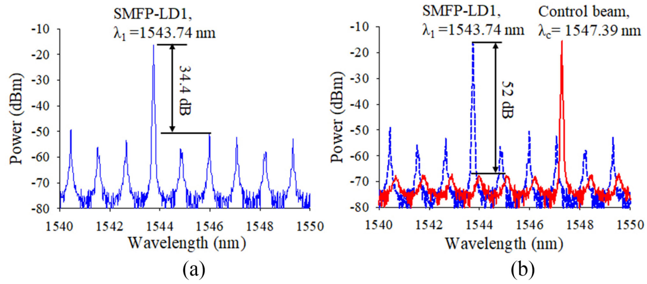

Fig. 3. Optical spectrum of switching between control outputs: (a) when external input $\lambda_c = 0$, the output of control unit is λ_1 and (b) when external input $\lambda_c = 1$, the output of control unit is λ_c.

way that λ_c provides positive wavelength detuning to any of the modes of SMFP-LD1 and negative wavelength detuning to that of the SMFP-LD2. Depending upon the power level, absence, and presence of the control beam, generation of RF signals at the output can be changed from single RF signal (millimeter wave) to simultaneous multiple RF signals (millimeter wave and micrometer wave) or to only microwave signal [26]. In the following sections, we will present the separate analysis of control unit, generating unit and finally with the whole configuration that provides the switching of RF generation based on the input control beam. First, we analyze the control unit, which is a simple switch that switches the output of the control unit from λ_1 to λ_c. Secondly, we analyze the RF generation with three conditions of input control beam: (i) absence of control beam ($\lambda_c = 0$), (ii) presence of control beam with strong injection locking (dominant mode of SMFP-LD1 is suppressed, $\lambda_c = 1$) and (iii) weak injection locking (control beam as well as the dominant mode of SMFP-LD exist at the output of the SMFP-LD1). Thenafter, we show the switching of RF generation at the output with the speed of 2 Gbps control signal to verify the fast switching on RF generation based on the control signal input, either logic ‘1’ or logic ‘0’.

A. Switching Between Control Outputs (Either λ_1 or λ_c)

The output of the control unit decides the switching of generation of RF signal at the output. The control unit is a simple ON/OFF switch which either provides the dominant mode of the SMFP-LD1, λ_1 or the external injected beam, λ_c, as a control signal that is injected to SMFP-LD2 with negative wavelength detuning. The input control signal is injected to SMFP-LD1 with positive wavelength detuning. When λ_c is absent, the SMFP-LD1 provides the dominant mode of SMFP-LD1 as a control output as shown in Fig. 3(a) with the SMSR of 34.4 dB. When the external beam, λ_c, is injected to SMFP-LD1, the dominant mode of SMFP-LD1 is suppressed providing ON/OFF contrast ratio of 52 dB due to injection locking phenomena as shown in Fig. 3(b). In this case, the only beam present at the output of the control unit is λ_c. Hence, with the presence and absent of the external injected beam, λ_c, the output of the control beam is switched between λ_1 and λ_c. Depending on the control output the generation of RF signal switch from one to another. The wavelength of the outputs of control unit (λ_1 and λ_c) can be changed by varying the operating temperature of SMFP-LD1

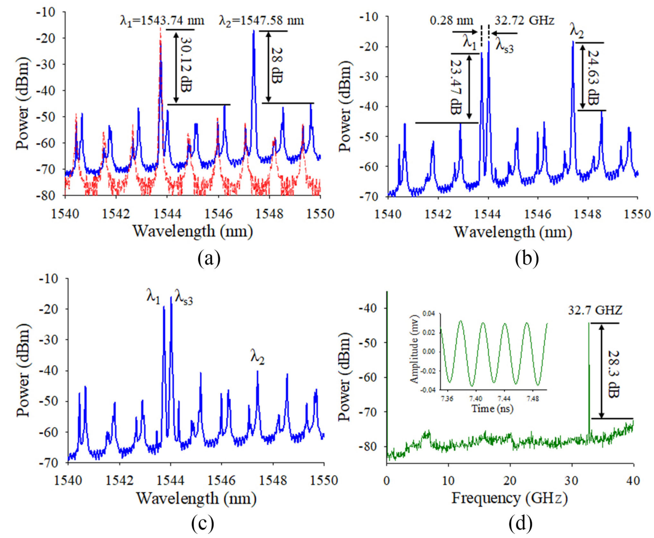

Fig. 4. RF generation when the control beam λ_c is “0”. (a) Dominant mode of SMFP-LD1 is injected to SMFP-LD2 (blue solid line), (b) simultaneous generation of two RF signals, (c) generation of microwave only, and (d) ESA and RTO diagram of RF signal of (c).

and changing the wavelength of the injected beam. This will provide the range of the frequency of the RF signal generation. The control input is modulated with 2 Gbps, NRZ data to verify the fast switching of RF generation which is discussed in detail in the latter section. In the proposed scheme, the control unit consists of a simple switch, which can be extended to a decoder. With the inclusion of a decoder in the control unit, multiple outputs can be obtained at the output and hence switching of the RF generation between multiple RF signals can be achieved.

B. RF Generation and Frequency Hopping With the Absence of Control Beam, $\lambda_c = 0$

When the control beam $\lambda_c = 0$, the only beam injected to the SMFP-LD2 is the dominant mode of SMFP-LD1, λ_1. λ_1 can be tuned in such a way that λ_1 can be either injected to the dominant mode of SMFP-LD2, λ_2, or any other side modes of SMFP-LD2 with negative wavelength detuning. It is noted that all injected beams into the SMFP-LD2 are mode locked and have negative wavelength detuning with the corresponding mode whether the beams are injected to the dominant mode or to the side modes. Since beams are injected with negative wavelength detuning, RF signals with good output performances and better linewidth can be generated through an optical beating in PD using SMFP-LDs [26], [28]. In the experiment, λ_1 is set in such a way that it is injected to the 3rd side mode, λ_{S3}, (left from the dominant mode of SMFP-LD2) with the wavelength detuning of 0.26 nm as shown in Fig. 4(a). The power of λ_1 is set in such a way that it is not sufficient to suppress the dominant mode, as a result, the RF signal of 478.43 GHz corresponding to the wavelength difference of 3.81 nm is possible by the optical beating of λ_1 and λ_2. This is due to the injection of λ_1 with negative wavelength detuning to the modes of the SMFP-LD2; as a result, the dominant mode of SMFP-LD2 is not suppressed. Since the dominant mode of SMFP-LD can be tuned to 10 nm range, by varying the dominant mode, RF signals of different frequencies can be obtained because it changes the wavelength detuning. Simultaneous multiple RF signals are possible if λ_1 is injected to any of the side modes of the SMFP-LD2 with proper power management as shown in Fig. 4(b). When the power of λ_1 is increased from -14 dBm to -11 dBm, the corresponding side mode, which is 3rd side mode (left side) gains the sufficient power for the optical beating between λ_1 and 3rd side mode, λ_2 and 3rd side mode and λ_1 and λ_2 as shown in Fig. 4(b). The optical beating of λ_1 and 3rd side mode gives the microwave of 32.7 GHz whereas two other RF signals of 445.71 GHz and 478.43 GHz are also obtained by the optical beating of λ_2 and λ_{S3} and λ_2 and λ_1, respectively. On further increasing the power of λ_1 to -9 dBm, λ_1 suppresses the dominant mode of SMFP-LD2 more than 26 dB, as a result, the only microwave of 32.7 GHz exists as shown in Fig. 4(c).

In this way, by changing the power of the λ_1, the transition from a millimeter wave to simultaneous generation of multiple RF signal and microwave only can be obtained. This phenomenon can be observed with the injection of any beam to the side modes of the SMFP-LD2. The only requirement is to maintain the negative wavelength detuning with the side modes of the SMFP-LD2. The ESA and real-time oscilloscope (RTO) diagram of the generated microwave by the beating of the dominant mode and the third side mode is shown in Fig. 4(d). The signal to noise power ratio of 28.3 dB and the linewidth of 165 kHz of output RF signal are obtained. The electrical domain results for higher frequencies RF signals are not shown due to the limitation on the maximum measurement range of the ESA, RTO, and the photodiode.

C. RF Generation With Control Beam, $\lambda_c = 1$ With Strong Injection Locking to SMFP-LD1

Next, we inject control beam, 1547.39 nm, to the 3rd side mode (right side of the dominant mode) of SMFP-LD1with positive wavelength detuning of 0.33 nm. With the injection of control beam, $\lambda_c = '1'$, the dominant mode of SMFP-LD1, λ_1, is suppressed with an ON/OFF contrast ratio of 52 dB as shown in Fig. 5(a). Fig. 5(b) shows the output of SMFP-LD2, which has the dominant mode at the wavelength of 1547.55 nm. The only beam injected to SMFP-LD2 is λ_c, which has the negative wavelength detuning of 0.16 nm to that of the dominant mode of SMFP-LD2 as shown in Fig. 5(c). On increasing the power of λ_c, the power of λ_c increases rather than suppressing λ_2, as shown in Fig. 5(c), which is due to the negative wavelength detuning. As a result, RF signal of 20.4 GHz (equivalent to that of the wavelength detuning of 0.16 nm) is generated as shown in Fig. 5(d). The ESA and RTO results for the generated microwave signal of 20.4 GHz with the signal to noise power ratio of 41.7 dB are shown in Fig. 5(d). In this case, the obtained linewidth is 117 kHz. The control beam can be tuned to any other wavelengths, the only requirements are maintaining the positive wavelength detuning to the modes of SMFP-LD1 and negative wavelength detuning to the corresponding mode of SMFP-LD2. Since the control beam is injected to the dominant mode of the SMFP-LD2 as shown in Fig. 5(c), simultaneous generation of

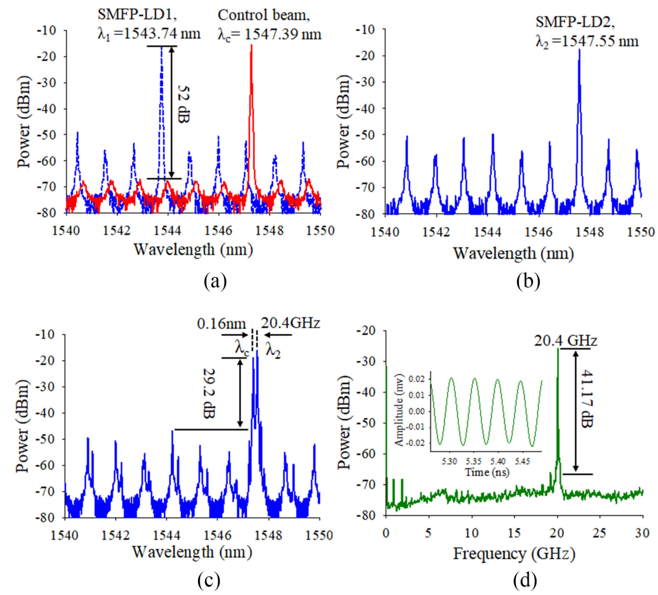

Fig. 5. RF generation when control beam λ_c is "1". (a) Suppression of the dominant mode of SMFP-LD1 with the presence of control beam with positive wavelength detuning, (b) output spectrum of SMFP-LD2 without any beam injection, (c) microwave generation due to optical beating of output of SMFP-LD1, control beam, and the dominant mode of SMFP-LD2, and (d) ESA and RTO diagram of microwave generation of (c).

RF signals are not possible in this case. However, if control signal wavelength is injected to any other side modes of the SMFP-LD2, a similar phenomenon as discussed in section 3(i) (generation of millimeter-wave only, simultaneous microwave and millimeter wave and microwave only) can be obtained by varying the power of the control beam.

D. RF Generation With Weak Injection Locking of Control Beam to SMFP-LD1

Weak injection locking refers to the injection of the external beam to SMFP-LD where the power of the external beam is controlled in such a way that the dominant mode of SMFP-LD is not suppressed. Hence, both injected beam λ_c and dominant mode λ_1 exist in weak injection locking. On weak injection locking of control beam in SMFP-LD1, λ_1 and λ_c are two beams that are injected to SMFP-LD2. SMFP-LD1 and SMFP-LD2 are tuned to new dominant modes (wavelengths of 1545.87 nm and 1546.11 nm to show the tunability of the dominant mode of SMFP-LDs. The control beam, λ_c, is set at 1549.13 nm, which lies on the 3rd side mode (right side from the dominant mode) of SMFP-LD2. Due to the weak injection locking of the control beam, the dominant mode of SMFP-LD1 ($\lambda_1 = 1545.87$ nm) exists at the output which lies on the dominant mode of SMFP-LD2. This provides negative wavelength detuning of 0.24 nm and 0.1 nm with the dominant mode and third side mode of SMFP-LD2, respectively as shown in Fig. 6(a). When the control beam is zero, λ_1 is the only beam injected to SMFP-LD2 as a result only two dominant modes are present at the output of SMFP-LD2, which is shown by the dotted blue line in Fig. 6(a). The maximum power difference between desired optical beams for optical beating to generate the RF signal is below

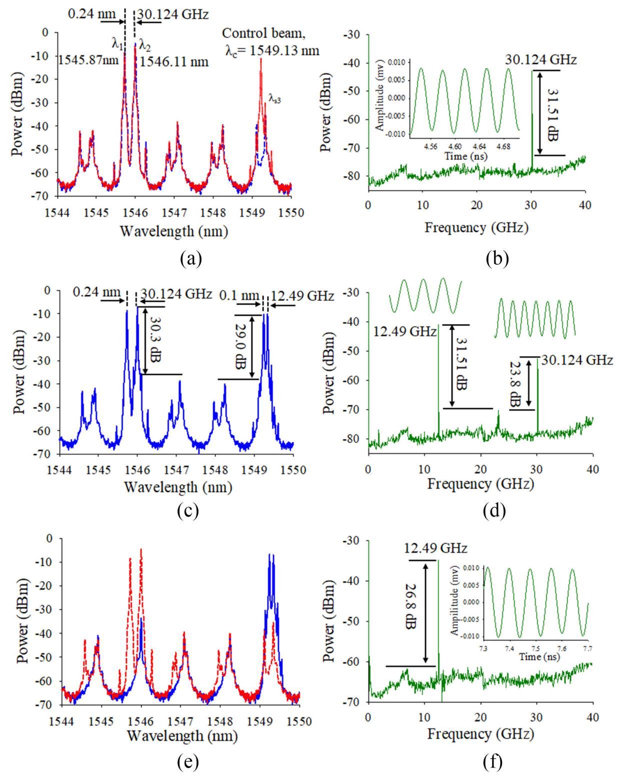

Fig. 6. RF generation when control beam λ_c is weakly injected to SMFP-LD1. (a) Output from SMFP-LD2 when the control is absent, (b) ESA and RTO diagram of RF signal of (a), (c) output spectrum from SMFP-LD2 with weak injection locking of control signal on SMFP-LD1, (d) ESA and RTO diagram of RF signal of (c), (e) output spectrum of weak injection locking with increase in power of control signal i.e., strong injection by control signal, and (f) ESA and RTO diagram of RF signal of (e).

5 dB whereas the minimum power difference between desired beams to the undesired beam is more than 23 dB. When the control beam in ON ("1") with weak injection locking, λ_1 and λ_c are two beams that are injected to SMFP-LD2. Due to the weak injection locking, the dominant mode of SMFP-LD1 is present even with the presence of control beam. The red solid line in Fig. 6(a) shows the spectrum output from SMFP-LD2 with weak injection locking.

Fig. 6(b) shows the respective ESA and RTO diagram for the RF signal generation by an optical beating of λ_1 and λ_2, which is equivalent to 30.124 GHz. The control signal, λ_c, which is injected to SMFP-LD1 and further to the 3rd side mode of the SMFP-LD2 has the wavelength detuning of -0.1 nm with the SMFP-LD2. The power of λ_c is increased in such a way it does not suppress the dominant mode of SMFP-LD1 but is sufficient to increase the power of λ_{s3} to generate RF signals by optical beating of injection locked beams, λ_c and λ_{s3}, as shown in Fig. 6(c). Hence, RF signal of 30.124 and 12.49 GHz are obtained through optical beating between λ_1 and λ_2 and λ_c and λ_{s3}, respectively. The ESA and RTO result for this case is shown in Fig. 6(d). Besides these RF signals, RF signals of higher frequency corresponding to the wavelength difference of λ_1 and λ_c, λ_1 and λ_{s3}, λ_2 and λ_c, and λ_2 and λ_{S3} are not shown in Fig. 6(d) due to instrument limitation. On increasing the power of control beam, SMFP-LD1 goes to strong injection locking which is shown in Fig. 6(e). The minimum signal to noise power ratio of more than 26 dB is observed for RF generation with weak injection locking. The linewidth of about 154 kHz and 95 kHz is obtained for the RF signal of 30.124 GHz and 12.49 GHz, respectively. In order to maintain the weak injection locking in SMFP-LD1 as well as to increase the power of λ_c (while injecting to SMFP-LD2), the power of λ_c is increased only after SMFP-LD1. With the change in power of λ_c, the three scenarios of millimeter wave, simultaneous millimeter and microwave and microwave are achieved as shown in Fig. 6.

E. Frequency Tuning and Stability Measurement of Beating Wavelengths, Output Frequency and Power Over the Time Interval

In order to verify the tunable range of the generated RF signal, we vary the wavelength detuning of the injected beam to SMFP-LD2. The minimum wavelength detuning we observed in this experiment is -0.02 nm, which is equivalent to the resolution of optical spectrum analyzer. The wavelength detuning can be of any value from 0.02 nm to full modal linewidth to the farthest mode of SMFP-LD for the generation of RF signal. When the negative wavelength detuning is more than half of the mode spacing, i.e., more than -0.56 nm, the injected beam behaves like a positive wavelength detuning to the previous side mode. Hence, it works as an injection locking with positive wavelength detuning to the previous side mode without suppression of the dominant mode known as weakly injection locked. In this case, the RF signal can be generated by beating the injected beam and the dominant mode. Thus, by varying the wavelength detuning and injecting beam to farther side modes, the frequency range of the generated RF signal can be changed from few GHz to several THz. The maximum RF frequency up to 42.5 GHz is shown in Fig. 7(a) due to the measurement limitation of ESA. The higher frequency generation can be verified by the optical spectrum results demonstrated in previous Sections III-B to III-D. The minimum power difference of RF signal to other frequency components is higher than 26 dB.

The wavelength shifting, frequency shifting and power variation are measured over a time of 1 hr to verify the performance of the generated RF signals. We did not observe any wavelength shift with in the maximum resolution of OSA (within the range of 0.02 nm). The maximum frequency variation over a time of 1 hr is found to be within the range of 5 MHz, which is shown in Fig. 7(b). Fig. 7(c) shows the power variation of the generated RF signals which are observed within the range of 1 dB. The further reduction on the frequency variation can be obtained with better temperature stable mechanism, frequency locking mechanism such as using combs, feedback injection locking, and side band injection locking. Nevertheless, further analysis are desired for increasing the frequency stability and better output performance of the RF signal.

F. Switching and Controlling of RF Generation With Modulated Control Signal

Next, we demonstrate the switching of RF generation with a control signal of 2-Gbps, 16-bit NRZ data pattern for strong

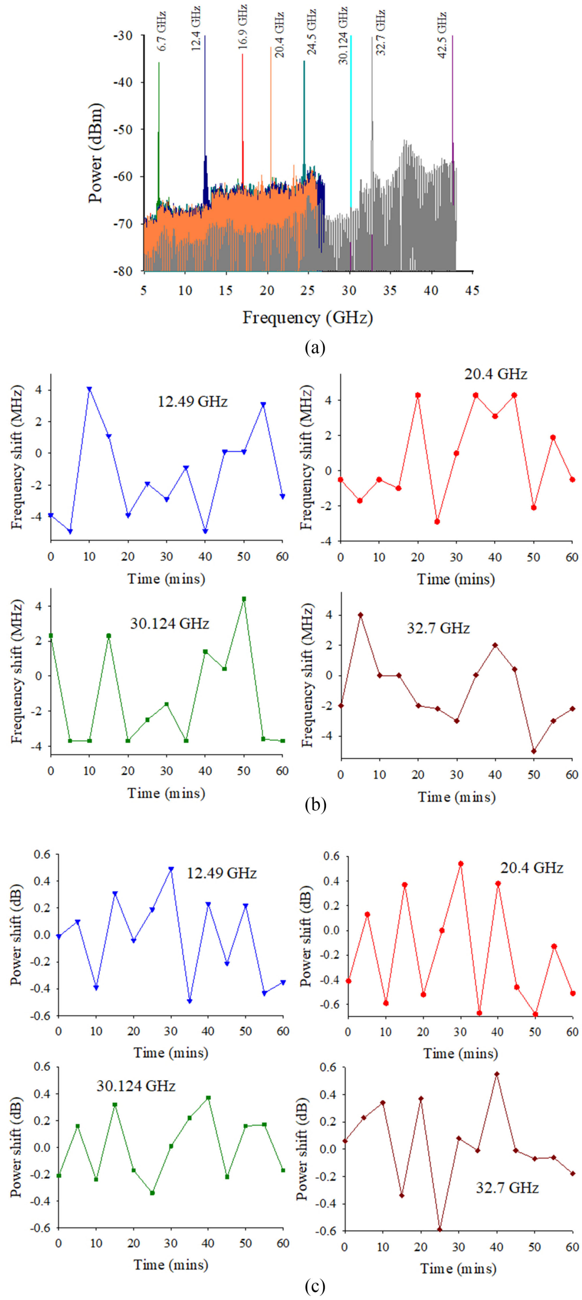

Fig. 7. Performance of generated RF signal: (a) different frequency of RF signals, (b) frequency variation, and (c) power variation.

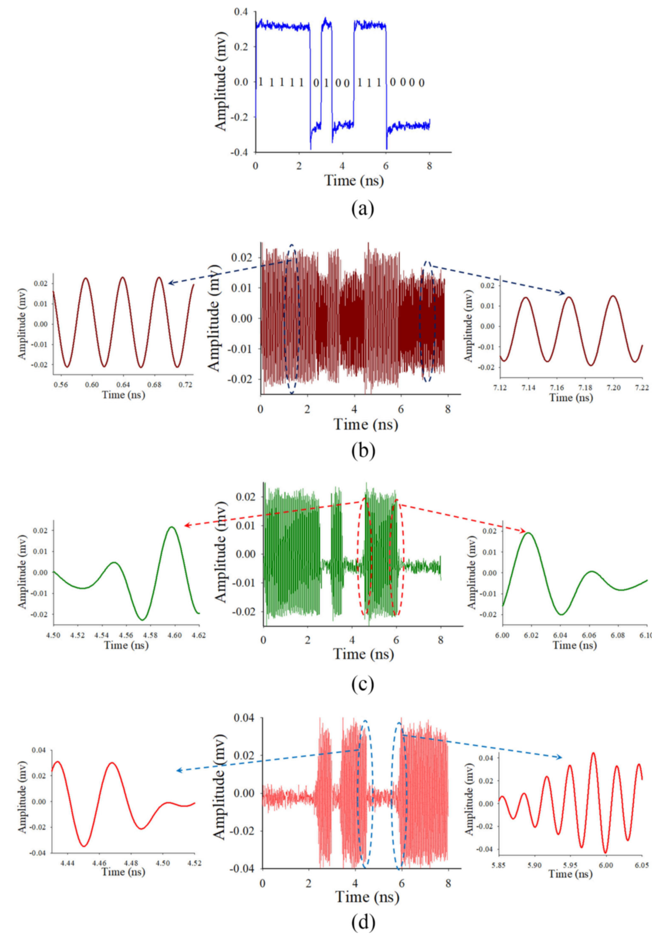

Fig. 8. Oscilloscope traces for (a) 16-bit, 2-Gbps NRZ control signal. (b) Switching of RF generation between (c) output from port 1 and (d) output from port 2.

injection and weak injection locking phenomena. We used 1111101001110000, 16-bit pattern for the demonstration of switching under strong injection locking as shown in Fig. 8(a) where '1' indicates the presence of control beam and '0' indicates the absence of control beam. As we discussed in previous sections with the OSA and ESA results, when $\lambda_c = '0'$, the dominant mode of SMFP-LD1, λ_1, the dominant mode of SMFP-LD2, λ_2, and 3rd side mode of SMFP-LD2, λ_{s3}, exist. On increasing the power of λ_1, the dominant mode of SMFP-LD2 is suppressed and hence only the beating of λ_1 and λ_{S3} is possible, as a result, RF signal of 32.7 GHz is obtained as discussed in Section III-A. When $\lambda_c = '1'$, RF signal of 20.4 GHz is obtained through the beating of the control beam, λ_c, and dominant mode of SMFP-LD2, λ_2, as discussed in Section III-B. With the presence (data sequence $'1'$) and absence (data sequence "0") of control signal, the RF signal generation is switched from one RF signal to another with the frequency of 20.4 GHz to 32.7 GHz as shown in Fig. 8(b). The frequency of RF signal can be easily tuned to another by changing the dominant mode of SMFP-LD1, the wavelength of injected beam, and the dominant mode of SMFP-LD2. And the RF output sequences depend upon the input control bit sequences. The generated signal is analyzed separately by placing filters at the output ports. The output of port 1 gives the RF signal with the frequency of 20.4 GHz which is generated when the control signal is present whereas the output port 2 gives the RF signal with the frequency of 32.7 GHz when the control signal is absent as shown in Fig. 8(c) and (d), respectively. We measure the rising and falling time in all three cases and found below 40 ps.

We modify the pattern of the control signal to 0011110011001011 for weak injection locking as shown in Fig. 9(a) in order to verify that the proposed scheme is independent of input data patterns. In weak injection, when $\lambda_c = '0'$, the RF signal due to the optical beating of dominant mode of SMFP-LD1 and SMFP-LD2 is generated as discussed in

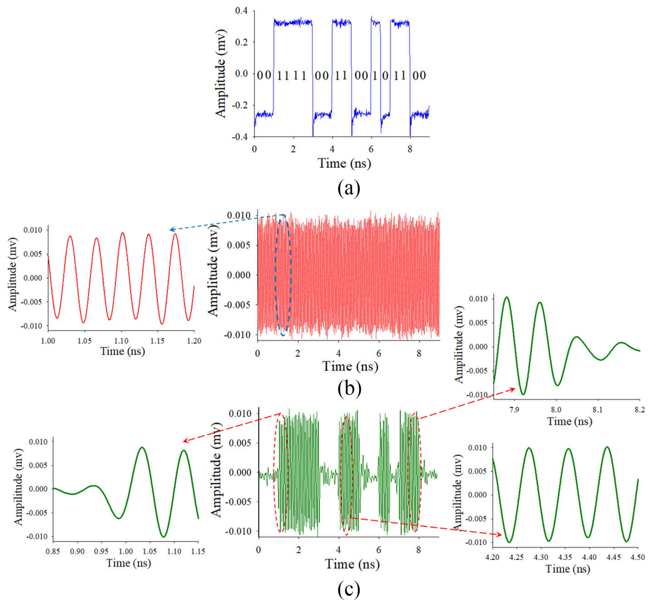

Fig. 9. Oscilloscope traces of (a) 2-Gbps, 16-bit NRZ control signal, (b) output from port 1, and (c) output from port 2.

Section III-C. When $\lambda_c = '1'$, two beams λ_c and λ_1 are injected to SMFP-LD2 in contrast to strong injection where only one beam is injected to SMFP-LD2. Since one beam is injected to the dominant mode and another to the side mode of SMFP-LD2, two microwaves can be generated along with four high-frequency RF signals. The optical beating of λ_1 and λ_2 occurs in both cases, whether there is a presence or absence of λ_c. Hence, in Fig. 9(b), the RF signal of 30.124 GHz is obtained in both cases; $\lambda_c = '0'$ and $\lambda_c = '1'$. The output from port 1 which is shown in Fig. 9(b) is the output signal after the filter and PD. The filter is tuned around the dominant modes of SMFP-LDs with sufficient bandwidth to pass both dominant modes. Hence, only the RF of 30.124 GHz is observed. It is noted that when $\lambda_c = '1'$, RF signal of 12.49 GHz is generated due to the optical beating of λ_c and λ_{s3} which is outputted from port 2 and shown in Fig. 9(c). In port 2, the center frequency of the filter is tuned around λ_c and λ_{s3} with the sufficient bandwidth to pass both signals. The rising falling time of generated RF signal is about 60 ps in this case.

IV. Conclusion

In this paper, we demonstrated a novel method of switching and controlling the frequency of the RF signal at the stage of RF signal generation using SMFP-LDs. In this method, frequency of generated RF signal is switched from one RF frequency/band to another RF frequency/band based on the control signal. A single external control signal controls the frequency switching of the generated RF signal as well as acts as one of the beating wavelengths needed for the RF generation. As a result, in the proposed method, there is no need for a separate scheme of generating RF signal at first before switching. We analyzed all three possible cases with different states of control signal: (a) absence of control signal, (b) presence of control signal, (c) weak injection locking by the control signal. The control signal is modulated with a 2-Gbps, 16-bit NRZ with different bit streams for strong injection and weak injection and observe that the proposed scheme of switching of RF generation is independent of the input bit pattern. The generated RF signals have good spectral output, high signal to noise power ratio, smaller linewidth, stable wavelengths, frequency, and power, and short switching time. The observed switching time is below 40 ps in strong injection and below 60 ps in weak injection case. The faster switching time and spectral output of the RF signals verify the successful demonstration of the proposed method of switching of RF generation at the speed of 2 Gbps. In the proposed method, the sequence of the frequency of the generated RF signal at the output can be varied by simply changing the input bit patterns. Increasing the number of control beams through the usage of a decoder as a control unit within the same framework, switching between multiple frequency of RF signal can be obtained. In addition, the propose scheme of switching of RF generation can be implemented to other techniques of RF generation. Such flexibility and re-configurability facilitates the generation of random RF signals at the output, which are essentials for secure communication. Further analysis of switching between multiple RF frequencies, generation of multiple RF output, and reducing the frequency variation of RF generation will be interesting to investigate in future.

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