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# A Monolithically Integrated Two-Section Laser for Wideband and Frequency-Tunable Photonic Microwave Generation

Qiang Cai, Yunshan Zhang, Jilin Zheng, Yamei Zhang, *Member, IEEE*, Pu Li, K. Alan Shore, *Senior Member, IEEE,* and Yuncai Wang

***Abstract*—A monolithically integrated two-section laser is presented for wideband and frequency-tunable photonic microwave generation. The laser consists of two back-to-back DFB sections forming a mutually coupled structure. By properly adjusting the bias currents of two sections, the laser can stably work at the state of period-one oscillation over a wide range of frequency detuning. Based on this, continuous and linear tuning of photonic microwave signals can be achieved. Experimental results confirm that a large tunable range from 12.45 to 80.30 GHz can be realized using this laser.**

***Index Terms*—Photonic microwave generation, monolithic integrated circuits, mutually coupled laser, period-one oscillation.**

## I. Introduction

Microwave oscillators are crucial components for wireless and mobile communication systems. With the increasing capacity demand of high-speed interactive multimedia services, there is a pressing need for microwave signal generation systems that can operate at high frequencies and with an ultrawide bandwidth [1], [2]. Conventional electronic microwave oscillators usually have a low frequency at the level of GHz. For higher frequencies, they experience rapid performance degradation due to the introduction of multiple stages of frequency doubling [3].

To overcome this issue, microwave signal generation using photonic approaches has attracted much research interest due to its advantages such as high bandwidth, low power consumption and high reliability [4]. Various photonic schemes for microwave generation have been studied, but they are mainly based on six different mechanisms or devices: direct modulation [5], [6], external modulation [7], [8], optoelectronic oscillators (OEOs) [9], [10], optical heterodyne [11]-[13], dual-mode lasers [14]-[17], and period-one (P1) nonlinear dynamics in semiconductor lasers [18]-[30]. For the schemes based on direct and external modulation, their generated microwave signals usually have a limited frequency by the relaxation oscillation of the used semiconductor laser or the modulator bandwidth [5]. OEO-based schemes can improve this problem, but they usually are at the cost of increasing the system complexity [9]. The optical-heterodyne-based approaches detecting two independent lasers with different wavelengths can easily produce high-frequency microwave signals, but their phase noise is very high because the two lasers commonly are not phase correlated [12]. Using a dual-mode laser can emit simultaneously two lasing modes with locked phase so that their generated microwave signals process a high spectral purity. However, this approach using the dual-mode lasers has a poor tuning ability due to the fixed frequency spacing between the two lasing modes [14].

Compared with these techniques mentioned above, the P1-based method offers some unique advantages for photonic microwave generation: (i) this method is an all optical scheme with a simple configuration and thus not suffering from limited electronic bandwidths [22]. (ii) The microwave frequency generated by P1 oscillation can be broadly tuned from a few to tens of GHz by simply adjusting the strength and detuning-

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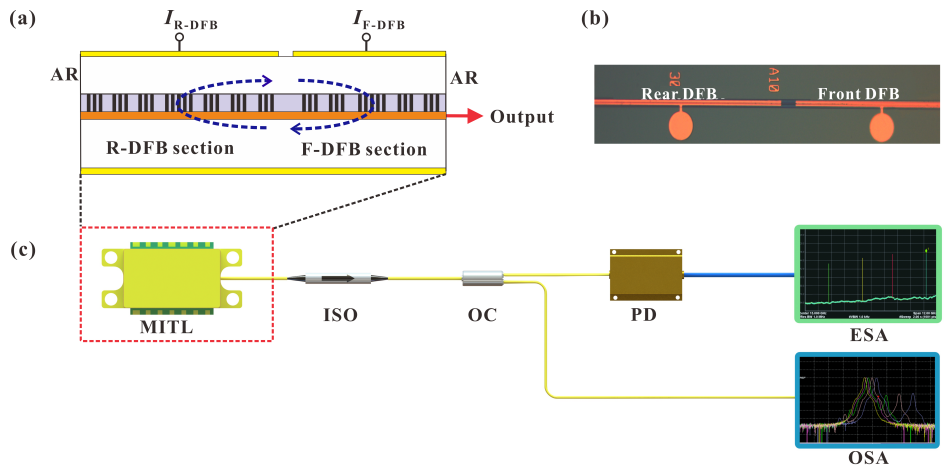


**Fig. 1.** (a) Schematic diagram of the MITL, (b) Photograph of the MITL, and (c) Experimental setup for generating and measuring the photonic microwave signals. MITL: monolithically integrated two-section laser; IOS: isolator; OC: 90:10 optical coupler; PD: photodetector; ESA: electric spectrum analyzer: OSA: optical spectrum analyzer.

frequency of the optical injection [23]-[26]. (iii) this technique has a single sideband (SSB) optical spectra structure and thus the associated microwave signals have the merit of low phase noise [27]. Although outstanding progresses the photonic microwave generation utilizing P1 nonlinear dynamics have been made, most of reported P1-based schemes are constructed using discrete optical devices and thus their whole systems are bulky and unstable.

In recent years, photonic integrated chips (PICs) show the potential for greatly reducing the system complexity and size of the P1-bassed microwave generation schemes [31]. Typically, there are two kind of integration schemes for P1 oscillation. One scheme is the optically feedback laser [32]. However, this scheme has a very low tuning ranges of only a few GHz being limited by the insufficient parameter space. The other scheme is the optically injected laser [33]. Compared with the optical feedback scheme, this optical injection scheme enables broadly tunable microwave generation. However, the PICs based on optical injection usually consist of three sections (two laser sections and one phase section) up to now. The efficient length of the phase section is very sensitive to temperature variations [34], [35]. This will significantly affect the stability of the associated time delay between the two DFB sections, so that the continuous tuning range is very difficult to be enhanced further.

To solve the problem of insufficient tuning-range confronted by the P1-based technique, we propose a monolithic integrated two-section laser (MITL) in this paper for photonic microwave generation [36]-[39]. In contrast with the aforementioned PICs with optical injection, our MITL is constructed of two back-to-back DFB sections with a mutually coupled geometry and its structure is largely simplified. Experimental results show that this MITL can output wideband and frequency-tunable microwave signals by adjusting the bias current of these two DFBs. Quantitatively, its operation frequency can be continuously tuned from 12.45 to 80.30 GHz, which corresponds to a tuning range of about 68 GHz. Moreover, it should be emphasized that the frequency of photonic microwave increases linearly (not nonlinearly like in Ref. [33]), when we enhance the bias current of the associated DFB section. This is another merit of our two-section laser over the existing PICs for photonic microwave generation.

## II. Experimental Setup and Results

Figs. 1(a) and 1(b) show the schematic diagram and photograph of the MITL, respectively. The laser consists of a rear DFB (R-DFB) section of length 450 μm and a front DFB (F-DFB) section of length 350 μm, which are electrically isolated from each other. Both DFBs are monolithically integrated on an InGaAlAs multiple quantum well (MQW) material and grown on an indium-phosphide (InP) substrate in the epitaxial structure by a conventional two-stage metal organic chemical vapor deposition (MOCVD). The grating of R-DFB and F-DFB is made using the reconstruction-equivalent-chirp (REC) technique [40] and has an equivalent π phase shift to obtain a single longitudinal mode yield. Antireflection (AR) coatings with reflectivity of less than 1% are deposited on both facets. The two DFB sections are fabricated back-to-back with a mutually coupled structure, and they are driven by two independent currents labelled as $I_{R\text{-}DFB}$ and $I_{F\text{-}DFB}$ in Fig. 1(a). Finally, the generated photonic microwave signal comes out from the right side of the F-DFB section.

Fig. 1(c) illustrates the experimental setup for measuring the photonic microwave signal. The MITL is powered by two high accuracy current sources (ILX Lightwave LDX-3412), while its temperature is stabilized at 24.5°C with a thermoelectric controller (ILX Lightwave LDT-5412B). The photonic microwave output of the MITL passes through an isolator to prevent unwanted feedback disturbance and then is split into two parts by a 90:10 fiber coupler. One part (10%) is recorded by an optical spectrum analyzer (OSA, Yokogawa, AQ6370C), and the other part (90%) is detected by an electric spectrum analyzer (ESA, Rohde & Schwarz, FSW-50, 50 GHz bandwidth) after a high-speed photodetector (PD, Finisar, XPDV2120RA, 50 GHz bandwidth).

Before generating the microwave signal, we measure the optical spectra of the F-DFB section in the MITL. An ideal single mode

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operation is required for P1-based photonic microwave generation. Fig. 2 shows the measured optical spectra of F-DFB under different bias currents $I_{\text{F-DFB}}$ when the current of R-DFB is unbiased (i.e., $I_{\text{R-DFB}}$ = 0 mA). From it, we can confirm that the F-DFB always has a very high side-mode-suppression-ratios (SMSRs) about 60 dB. This means that this F-DFB does not generate redundant frequency components induced by the possible interactions between the main mode and other side modes. At the same time, it also can be observed that the lasing wavelength moves to the longer side with a tuning efficiency of 0.0093 nm/mA, when the bias current increases. The origin of the red-shift for free-running F-DFB in Fig. 2 is from the refractive-index change of the active region induced by the increased bias current [41]. In a free-running laser, the refractive index $n(I)$ of the active region is linear with the bias current $I$ and can be expressed as $n(I)= n_0+K_r (I- I_0)$. Note, $n_0$ is the refractive index when the injection current is $I_0$, while $K_r$ is a scale coefficient. Then, the associated wavelength shift $\Delta\lambda$ can be calculated as follows:

$$\Delta\lambda=\frac{\Delta n}{n_0}\lambda_0 \tag{1}$$

Note, $\Delta n$ is the effective refractive index change, and $\lambda_0$ is the lasering wavelength corresponding the bias current $I_0$.

We point that limited by the encapsulated package, the output of R-DFB cannot be directly measured, but it is expected that the R-DFB should also exhibit a single-mode oscillation when it works independently because it has the same grating structure as that of the F-DFB.

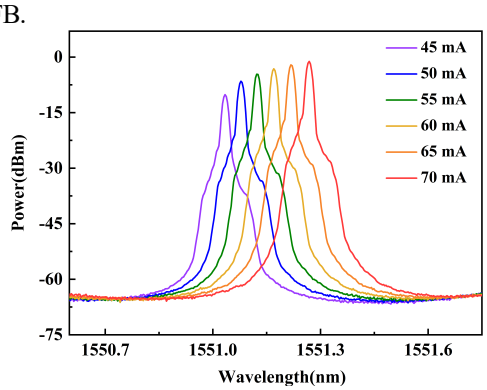


**Fig. 2.** Measured optical spectra of the free-running F-DFB. The bias current of $I_{\text{R-DFB}}$ is unbiased, and the current of $I_{\text{F-DFB}}$ is biased at 45 mA, 50 mA, 55 mA, 60 mA, 65 mA, and 70 mA, respectively.

Next, we consider photonic microwave generation. In the experiment, the bias current of the F-DFB is fixed at 60 mA, while the current injected into the R-DFB is adjusted in the range from 40 to 100 mA. Due to the temperature and carrier density variations, different frequency detuning between these two DFBs appears. Fig. 3 shows the associated optical spectra [left column] and the radio frequency (RF) spectra [right column] at different detuning frequencies. Fig. 3(a-i) depicts the measured optical spectrum when $I_{\text{R-DFB}}$ =40 mA and $I_{\text{F-DFB}}$ =60 mA. From it, we can see that the detuning frequency $\Delta f$ can be ignored, so the R-DFB are locked by F-DFB and thus the lasing wavelength of F-DFB can be observed. This does not mean that both the free-running F-DFB and R-DFB have the same lasing wavelength at different bias currents. In fact, there is a frequency detuning between the F-DFB biased at 60 mA and R-DFB at 40 mA. Due to its low bias current, the R-DFB with low power is injection-locked by the F-DFB with a large power. In consequence, only the lasing wavelength of F-DFB is observed. Note, the lasing wavelength of F-DFB moves to the longer side compared with its free-running state at the same condition in Fig. 2. Different with the free-running F-DFB in Fig. 2, the F-DFB in Fig. 3 is optically injected by another laser (i.e., the R-DFB). In this case of optical injection, the red-shift of the F-DFB wavelength is induced by the cavity resonance shift [42]. Specifically, with the increase of the optical injection strength (the bias current of the R-DFB), the optical gain deficit of the F-DFB increases. Due to the anti-guidance effect, the refractive index increases and thus the cavity resonance shifts red. In addition, its flat RF spectrum without any prominent peaks [Fig. 3(a-ii)] further confirm that the MITL indeed operates at a stable continuous wave (CW) state.

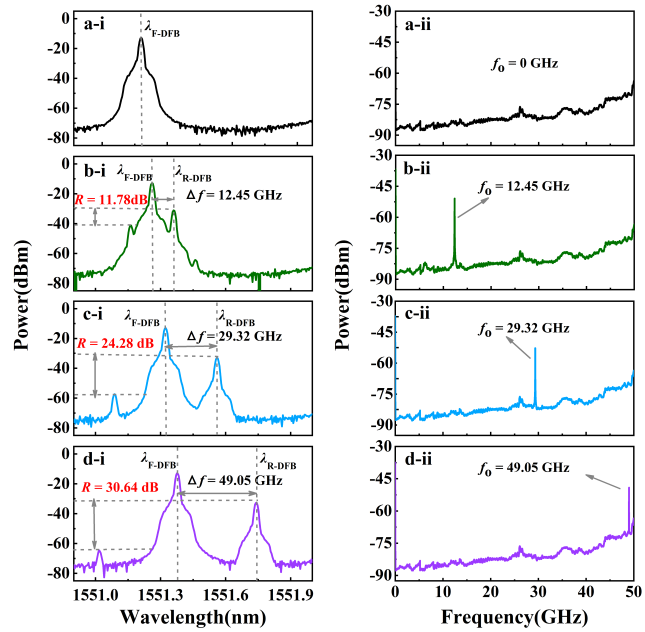


**Fig. 3.** Measured optical spectra (left) and RF spectra (right). The bias current of $I_{\text{F-DFB}}$ is fixed at 60 mA, and the current of $I_{\text{R-DFB}}$ is biased at (a) 40 mA, (b) 42.5 mA, (c) 55 mA, and (d) 71.6 mA, respectively.

When the bias current $I_{\text{R-DFB}}$ increases to 42.5 mA, the F-DFB is subjected to a relatively strong optical injection and a larger detuning frequency. Thus, the laser undergoes a Hopf-bifurcation to the state of P1 oscillation [43], as shown in Fig. 3(b). In this case, ones can find from Fig 3(b-i) that the optical spectrum is dominated by both the principal wavelength component of the F-DFB (labelled as $\lambda_{\text{F-DFB}}$) and the regenerated injection frequency of the R-DFB (labelled as $\lambda_{\text{R-DFB}}$). In consequence, the MITL operates at a single sideband (SSB) P1 oscillation, which is desirable for photonic microwave generation. Quantitatively, the P1 frequency $f_o$ is measured to be 12.45 GHz, which equals the after-injection detuning frequency $\Delta f$ between R-DFB and F-DFB [Fig. b(a-ii)].

Further increasing the bias current $I_{\text{R-DFB}}$, we can obtain a higher frequency of photonic microwave. For instance, when the bias current $I_{\text{R-DFB}}$ is increased to be 55 mA, the measured optical spectrum and RF spectrum are shown in Fig. 3(c). After calculation, the detuning frequency $\Delta f$ between R-DFB and F-DFB is 29.32 GHz [Fig. 3(c-i)], and accordingly the MITL generates a

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photonic microwave with a high frequency of 29.32 GHz [Fig. 3(c-ii)]. Limited by the measuring range of the available PD and ESA, the highest frequency 49.05 GHz of the generated photonic microwave is observed when $I_{\text{R-DFB}}$ is biased at 71.6 mA, as shown in Fig. 3(d).

We emphasize that in our method the microwave signal is generated by the period-one (P1) oscillation in the optically injected laser system, not optical heterodyne. Hence, there is a typical feature for P1 oscillation that under different operating conditions there are some side-bands in the optical spectra except for the principal oscillation [44]. In our experiment, the F-DFB and R-DFB are mutually injected each other and thus three different peaks in Figs. 3(b)-(d) appear as follows: (i) The two high peaks correspond to the principal oscillation $\lambda_{\text{F-DFB}}$ and injection frequency $\lambda_{\text{R-DFB}}$, respectively; (ii) The third peak represents another sideband. The frequency separation between the second sideband and principal oscillation $\lambda_{\text{F-DFB}}$ is the same as that between the principal oscillation $\lambda_{\text{F-DFB}}$ and injection frequency $\lambda_{\text{R-DFB}}$, indicating that the sideband is a harmonic signal of of the first sideband (i.e., injection frequency $\lambda_{\text{R-DFB}}$) due to the inherent nonlinearity of the optically injected lasers.

Furthermore, we point that all the measured RF signals are single-mode, as shown in Figs. 3(b-ii) to 3(d-ii). The physical mechanism behind the P1 oscillation can be viewed as the beating of two dominating wavelengths: one is regenerated from the optical injection while the other is emitted near the cavity resonance wavelength [43]. From the optical spectra in Figs. 3(b-i) to 3(d-i), we can determine that the two dominating wavelengths in our experiment is just $\lambda_{\text{F-DFB}}$ and $\lambda_{\text{R-DFB}}$. Therefore, only a single mode exists in the associated RF spectra in Figs. 3(b-ii) to 3(d-ii). In theory, the second harmonic induced by the second sideband and $\lambda_{\text{R-DFB}}$ could produce another microwave tone. However, the high sideband suppression ratio $R$ at least higher than 10 dB [Figs. 3(b-i) to 3(d-i)]) make the possible second harmonic be so weak that it will be submerged in background noise in practice. Note, $R$ is quantitatively defined by treating the laser as a two-wavelength light source: The weaker of the two dominating modes is firstly chosen and then compared with the strongest component among the rest sidebands. The obtained power difference in dB is $R$. This can be also be confirmed from Fig. 3(b-ii) where there is no observable peak corresponding to the second harmonic at the frequency of 24.9 GHz (=2×12.45 GHz).

As demonstrated in [45], the delay time plays a critical role on the stability of the RF signal formation in a mutually coupled semiconductor lasers system. We can find that for low values of delay time, undesired states for microwave signal generation such as period-two (P2), quasi-period (QP) and chaotic oscillation can be greatly suppressed in a large current-tuning range. In our scheme, the back-to-back mutually coupled structure can guarantee that there is no time delay between the F-DFB and B-DFB. Thus, our monolithically integrated laser can output P1 oscillation in a very large region. In our experiment, the F-DFB is biased at 60 mA, while the current of the R-DFB ($I_{\text{R-DFB}}$) can be tuned from 40 to 100 mA. Our results show that once the bias-current of the R-DFB is above 42.5 mA, our laser always keeps in the P1 state.

## III. Discussions

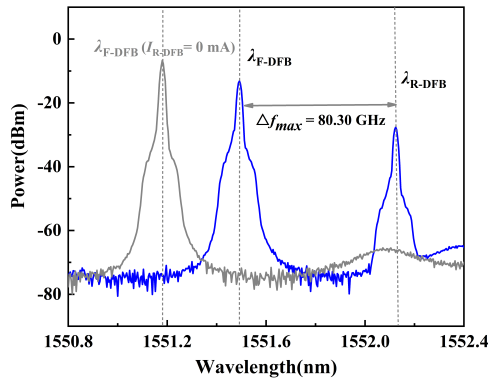


**Fig. 4.** Blue line: measured optical spectrum of the MITL with the maximal detuning frequency, where the current of $I_{\text{F-DFB}}$ is biased at 60 mA and the current of $I_{\text{R-DFB}}$ is biased at its available maximum current of 100 mA. Gray line: measured optical spectrum of the free-running F-DFB, which is the same as that in Fig. 2 when $I_{\text{F-DFB}}$ = 60 mA and $I_{\text{R-DFB}}$=0 mA, respectively.

Firstly, we discuss the physical limit of the obtainable photonic microwave signal using our laser. As the current $I_{\text{R-DFB}}$ increases in the experiment, the lasing wavelength of the R-DFB moves toward the longer wavelength obviously, while the wavelength of F-DFB changes slightly. From this point of view, the maximal detuning frequency can be expected when $I_{\text{R-DFB}}$ is set to be its available maximum current of 100 mA. Fig. 4 shows the associated optical spectrum. The optical spectrum of the laser in P1 oscillation has two significant characteristics different with that of a normal DFB laser: (i) the wavelength of the DFB laser in P1 oscillation has a red shift than that of the free-running normal DFB laser [45]; (ii) The linewidth of the DFB laser in P1 oscillation is wider than that of the free-running normal DFB laser [21]. To make this point clear, we insert the measured optical spectrum of the free-running F-DFB (grey line) in Fig. 4 in contrast with the optical spectrum of the MITL with the maximal detuning frequency (blue line). As can be seen, the wavelength of the F-DFB under injection indeed red-shifts from the free-running wavelength of 1551.179 nm to 1551.490 nm. Moreover, the linewidth of the F-DFB under injection is slightly broaden compared with that in free-running. This means that our MITL works at P1 state and thus can be viewed as the evidence of the microwave generation. From Fig. 4 (blue line), we can confirm the detuning frequency comes up to a high value of 80.30 GHz. That means that using the present MITL can output photonic microwave signal with the maximum frequency of about 80 GHz in principle.

Furthermore, the relationship between the after-injection detuning frequency $\Delta f$ with the bias current of R-DFB is investigated. Here, we point that the result above 50 GHz is calculated according to the measured detuning frequency between the two dominant modes, rather than the actual RF measurement. As illustrated in Fig. 5, solid dots are experimental data and the red dashed line is a fitted line. After calculation, the linearity $r^2$ between the detuning frequency $\Delta f$ and the bias current $I_{\text{R-DFB}}$ is as high as 0.99 [Note, $r^2$=1 for perfect linearity]. In other words, the MITL can generate continuously and linearly tuning microwave signals over a very large range. Such a high linearity

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can be explained as follows. The dynamical behaviors in mutually coupled lasers (MCLs) are mainly dependent on the detuning frequency, coupling strength and coupling delay [41], [42], [45]. Because of the back-to-back structure, there is no coupling delay in our MITL. So, the associated influence caused by coupling delay variation can be discounted. On the other hand, MCLs without coupling delay usually can realize the P1 oscillation in a large parameter region [45]. When MCLs operate at a significant detuning frequency (corresponding to a relatively strong injection), the system will be dominated by the detuning frequency and always exhibits P1 oscillation [46]. Considering that the bias current of the F-DFB is fixed, the detuning frequency is mainly determined by the red-shift induced by the cavity resonance shift due to the optical injection from the R-DFB [41], [42]. This cavity resonance shift increases almost linearly with the increase of the coupling strength [42]. The coupling strength is linear with the bias current of the R-DFB in our experiment, so the generated microwave signals can be linearly tuned in a very large range.

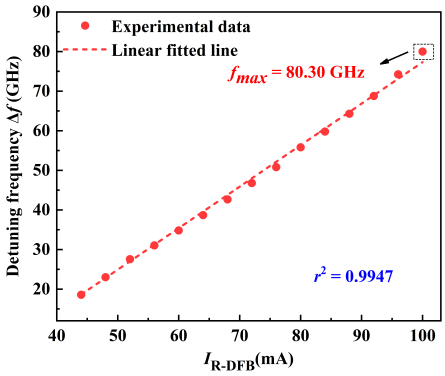


**Fig. 5.** The relationship between the optical detuning frequency $\Delta f$ with the current of R-DFB. The current of $I_{F\text{-}DFB}$ is fixed at 60 mA, and the current of $I_{R\text{-}DFB}$ is adjusted from 44 to 100 mA with a 4-mA step.

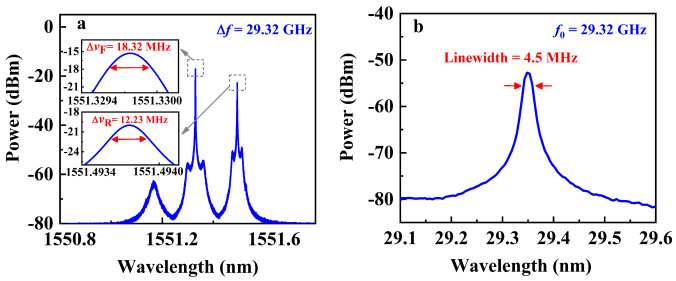


**Fig. 6.** (a) Measured optical spectrum and (b) RF spectrum when generated microwave frequency $f_0$ is about 29.32 GHz.

Figure 6 shows the measured optical spectrum and the associated RF spectrum when the generated microwave signal is about 29.32 GHz. Note, the optical spectrum in Fig. 6(a) is measured using an advanced optical spectrum analyzer (APEX AP2041B) with an ultrahigh resolution of 0.04 pm. After calculation, it can be determined that the linewidth $\Delta\nu_F$ and $\Delta\nu_R$ are 18.32 MHz and 12.23 MHz, respectively. From Fig. 6(b), it can be observed that the generated microwave signal has a much narrower linewidth of 4.5 MHz, which is less than the sum of the optical linewidths. This indicates that our horizontal integration of the DFB lasers with two optical modes sharing the same optical cavity can make their phase be partially correlated, and thus can increase the purity of the generated microwave signal.

Figure 7 shows the measured frequency variation of the generated microwave signal within 100 minutes. In the measurement, we recorded the center frequency of generated microwave signal every 5 minutes. It can be seen clearly from Fig. 7 that the frequency varies within a range of ±2.15 MHz, which is a relatively normal level for P1-based microwave generator. This long-term stability is expected to be significantly reduced from several MHz to KHz by further introducing external optical feedback [21, 23, 24, 28, 29, 31], optical injection [33], filtered feedback [34], or phase-locked loop [47]. This is the aim of our next work.

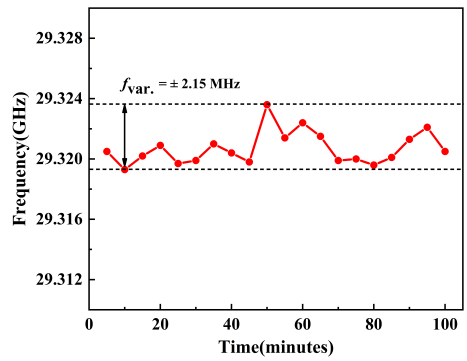


**Fig. 7.** Frequency stability of the microwave signal from MITL when the $f_0$ is 29.32 GHz. (Spectrum analyzer Setup: center frequency is set at 29.32 GHz, span is set at 100 MHz, RBW is set at 100 kHz).

We list some typical photonic integrated chips for photonic microwave generation in Table 1. In general, there are mainly two kinds of techniques that has been photonic integrated in a chip: optical heterodyne and P1 oscillation. From this table, one can see clearly that the generated microwave signal by optical heterodyne technique can reach up to the THz range by detecting two optical beams with different wavelengths. Typically, Dijk *et al.* realized millimeter-wave generation at up to 105 GHz based on heterodyning the optical tones from two integrated lasers [48]. Lo *et al.* proposed a monolithically integrated microwave frequency synthesizer where two tunable monochromatic lasers spectrally separated by 0-10.7 nm were realized [12]. Wei *et al.* demonstrated a widely tuning range of 1 GHz to 2.275 THz using feedback-cavities integrated two DBR lasers [13]. Kim et al. designed two monolithic dual-wavelength lasers with tuning ranges of 0.17- 0.79 THz [49] and 0.48 - 0.15 THz [50], respectively. However, it also must be pointed that the linewidths of the optical heterodyne microwave generator are very large (tens of MHz) corresponding to high phase noise levels. By contrast, the P1-based technique can greatly induce the phase noise of the generated microwave signal. Quantitatively, it can be confirmed from Table 1 that no matter the optical feedback laser [51] or optical injection laser [33], the linewidths of their generated microwave signals is at the level of few MHz. In particularly, we must emphasize that, different with the structure with three sections in [33], the elimination of phase section enables that our scheme not only has a simple structure and achieves a broad tuning range of tens or even hundreds of GHz. In sum, our scheme processes both two merits of the

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TABLE 1. COMPARISON OF PHOTONIC INTEGRATED LASER CHIPS FOR MICROWAVE GENERATION.

| Realization principle | Chip structure | Tuning range | Optical linewidth | RF Linewidth (before narrowing) | Ref. |
|---|---|---|---|---|---|
| Optical heterodyne | Two DFBs, an MMI coupler, eight SOAs, an electro-optical modulator and a UTC PD. | 5 to 110 GHz | / | / | [48] |
| | Two wavelength tunable DFB lasers, an MMI coupler and a PIN-PD. | 0-10.7 nm | 20 to 40 MHz | 90 MHz | [12] |
| | Two DBR-LDs, a feedback cavity, and two MMIs. | 1 GHz-2.275 THz | / | 11 MHz | [13] |
| | Two DFB sections, a phase section. | 0.17 to 0.49 THz | / | / | [49] |
| | A phase-shifted DFB section, a phase section, a DBR section. | 0.48 to 1.5 THz | 5.6 MHz | / | [50] |
| P1 oscillation | A DFB section, a phase section and an amplifier section. | 30 to 38 GHz | / | 3.7 MHz | [51] |
| | Two DFB sections and a phase section | 15 to 30 GHz | / | 1.9 to 3.2 MHz | [33] |
| | Two DFB sections | 12 to 80 GHz | Below 20 MHz | 4.5 MHz | Our scheme |

broad tuning range and low phase noise at the same time and thus has the potential to be widely used for microwave generation in practice.

## IV. Conclusion

In summary, we have proposed and demonstrated experimentally a MITL for photonic microwave generation. Based on P1 oscillation in the back-to-back coupled structure, this MITL can output wideband and frequency-tunable photonic microwave signals with a large operation frequency range from 12 to 80 GHz. Moreover, the frequency of generated microwave signals can be tuned by simply adjusting the bias current with a high linearity of 0.99. Considering its chip-scale size, simple structure and good performance, we believe that this MITL can be a promising candidate as a photonic microwave generator for many applications such as wireless communications and microwave photonic radars.

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