Laser Physics

PAPER

Tunable microwave generation utilizing monolithic integrated two-section DFB laser

Laser Phys. 29 (2019) 046201 (5pp) https://doi.org/10.1088/1555-6611/ab0367

Tunable microwave generation utilizing monolithic integrated two-section DFB laser

Yuke Zhou[1], Zuye Lu[1], Lianyan Li[2], Yunshan Zhang[2], Jilin Zheng[3], Yinchao Du[1], Linjie Zou[1], Yuechun Shi[1], Xing Zhang[4], Yongyi Chen[4] and Xiangfei Chen[1]

[1] College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, People's Republic of China
[2] College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210023, People's Republic of China
[3] College of Communications Engineering, PLA Army Engineering University, Nanjing, People's Republic of China
[4] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033, People's Republic of China

E-mail: yszhang@njupt.edu.cn and zhengjilinjs@126.com

Received 13 October 2018
Accepted for publication 23 January 2019
Published 26 February 2019

CrossMark

Abstract

Tunable microwave generation and frequency up-conversion are demonstrated utilizing a monolithically integrated two-section DFB laser. The frequency of the microwave signal is tuned from 13 GHz to 40 GHz, which can be further improved by adjusting the wavelengths of the DFB lasers. Utilizing the sideband optical injection locking technique, frequency-doubled microwave signals with low phase noise of −100.9 dBc/Hz at 10 kHz and narrow linewidth of 102 Hz are obtained. In addition, the tunable range of frequency-doubled and frequency-quadrupled microwave signals are also investigated respectively.

Keywords: microwave generation, monolithically integrated, optical heterodyne, optical injection locking

(Some figures may appear in colour only in the online journal)

1. Introduction

Photonic microwave generation is an important method to generate microwave signals with high performance. Comparing with the conventional electrical methods, the photonic methods can generate microwave signals with higher frequency and lower costs [1]. It has been implemented for applications such as broadband wireless access networks [2], lidar system [3], and all-optical clock generation [4]. Various techniques have been developed to generate photonic microwave signals such as direct modulation [5], mode locking [6], optoelectronic oscillators [7], optical phase lock loop [8] and optical heterodyne [9, 10], etc. Among them, the optical heterodyne method which generates microwave signals by the beating of two optical waves receives much attention due to its advantages in simplicity, and high frequency generation. In the early research of optical heterodyne, discrete lasers and various independent optical components were necessary to generate microwave signals [9, 10]. With the development of micro/nano-fabrication, monolithically integrated two-section DFB lasers are employed to generate microwave signals based on the optical heterodyne [11–15]. There are several difficulties in fabricating the two-section DFB lasers. Firstly, in order to obtain good microwave signals, both of the lasers should operate in single longitudinal mode (SLM) state. If gratings without phase shifts are utilized in the two-section DFB lasers [15], not all devices are suitable for photonic microwave generation. Particularly for the devices where one section operates in multimode state. In order to obtain high device yield, gratings with phase-shifts are utilized in the two-section DFB lasers, which should be fabricated by sophisticated fabrication schemes, such as the E-beam lithography technique [14]. Furthermore, the frequency of the microwave signal is equal to the frequency difference between the two sections. Hence, it is very important to control the wavelengths of the integrated two sections with high precision. For instance, if the wavelength spacing error of the two sections (at 1550 nm region) is 1 nm, the frequency error of the generated microwave signal is about 125 GHz. To our knowledge, it is quite a difficult task to control the wavelengths of DFB lasers with deviations less than 1 nm due to the mechanical error, even for the E-beam lithography technique [16].

In this letter, we report a microwave generator that can produce tunable and high-quality signals utilizing a monolithic two-section DFB laser. The gratings of the two-section DFB laser are sampled gratings with equivalent phase shifts, which can provide good SLM operation and precisely controlled wavelength with low fabrication costs [17]. Optical injection locking with an external radio frequency (RF) signal injected into the slave laser (SL) synchronizes the wavelengths of the two lasers. In the experiment, we demonstrate the generation of original beat signals and high-quality frequency-doubled signals with external RF signal injection. Both the linewidth and the phase noise of the beat signals are investigated. Furthermore, tunable frequency-doubled and frequency-quadrupled signals are achieved respectively.

2. Principle

The schematic of the two-section DFB laser is shown in figure 1. It consists two in-line DFB lasers including the master laser (ML) and the SL. The lengths of the two sections are $L_m = 650$ μm and $L_s = 650$ μm respectively. The ML and SL have a common active layer. The epitaxy of the device is grown by conventional two-stage metal organic chemical vapor deposition on an n-InP substrate. An n-InP buffer layer, an n-InAlGaAs lower optical confinement layer, an InAlGaAs multiple-quantum-well structure, a p-InGaAsP upper optical confinement layer and a p-InGaAsP grating layer are successively grown on an n-InP substrate in the first epitaxial growth. A conventional holographic exposure combining with conventional photolithography are used to form the sampled gratings. After the fabrication of the sampled grating, a p-InP cladding layer and a p-InGaAs contact layer are successively regrown over the entire structure in the second epitaxial growth. Then a conventional ridge waveguide processing is performed and p-metal contact windows are opened for metallization. The ML and SL are electrically isolated with each other and their bias currents are labeled as I_m and I_s. Finally, both facets of the devices are coated by anti-reflection (AR) coatings with reflectivity less than 1% to suppress the Fabry–Perot modes of the lasers [17].

The gratings in the proposed two-section DFB laser are designed with an identical seed grating period Λ_0. Strong grating strength is employed to reduce the interference between ML and SL. Equivalent phase shifts in the gratings are employed to ensure good SLM operation, and the lasing wavelengths of the two lasers are controlled by the sampling periods P_m and P_s [18]. Through tuning the sampling periods, we can easily obtain the required wavelength difference between the two lasers, i.e. the beat frequency generated by the optical heterodyne.

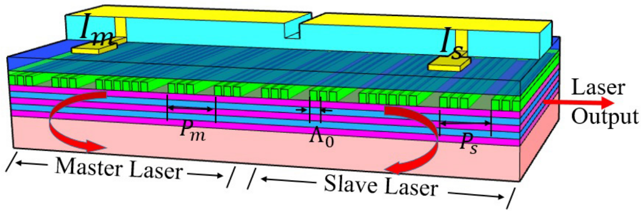

Figure 1. Schematic of the two-section DFB laser.

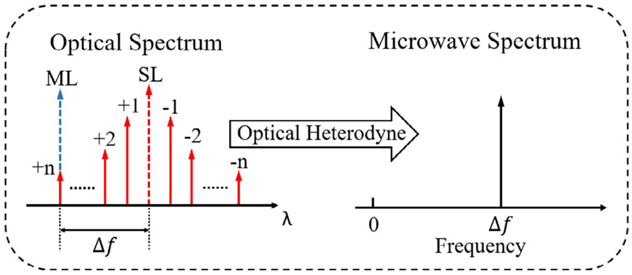

Figure 2. The simplified operational principle of optical injection locking for microwave generation in the two-section DFB laser.

When the light of the ML is injected into the SL, the two-section DFB laser can work in the states of unlocking, stable locking, periodic oscillation, and chaos, etc. These dynamics of the two-section laser are mainly determined by the injection ratio and the frequency difference between the wavelengths of the ML and SL. When the injected light from ML is weak, the two wavelengths of ML and SL can co-exist in the same cavity and a four-wave-mixing (FWM) output can be observed on the optical spectrum [19, 20]. The two main modes of ML and SL compose the main peaks of the output optical spectrum. When they beat in the high-speed photodetector (PD), a microwave signal with a frequency equal to the frequency difference of the two modes is generated. The frequency of the generated microwave signal can be calculated as [14]:

$$\Delta f = c\left(\frac{1}{\lambda_m} - \frac{1}{\lambda_s}\right), \tag{1}$$

where c is the speed of light, λ_m and λ_s are the emission wavelengths of ML and SL, respectively.

However, the beat signal generated by the free-running two-section laser suffers from the phase and frequency fluctuation due to the lack of phase correlation. This problem can be solved by the sideband optical injection locking technique [1]. Figure 2 shows the mechanism of the optical injection locking. When an RF signal modulates the SL, a series of sidebands will generate. Then, the optical signal of ML is injected to the SL, and locks the selected sideband of SL. Therefore, the optical phase of ML's main mode, SL's main mode, and the sideband of SL are synchronized [15]. Since the two peaks of the output optical spectrum are in phase, the beating of them in the PD would generate a microwave signal with low phase noise and narrow linewidth. In addition, frequency up-conversion can be achieved by injecting the optical signal of ML into high orders of SL's sidebands.

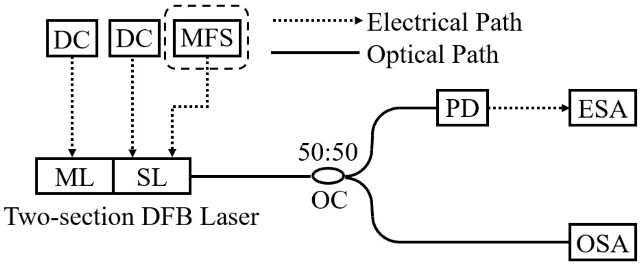

Figure 3. Schematic of the experiment setup. ML, master laser; SL, slave laser; DC, direct current; OC, optical coupler; PD, high-speed photodetector; ESA, electrical spectrum analyzer; OSA, optical spectrum analyzer; MFS, RF/microwave frequency synthesizer.

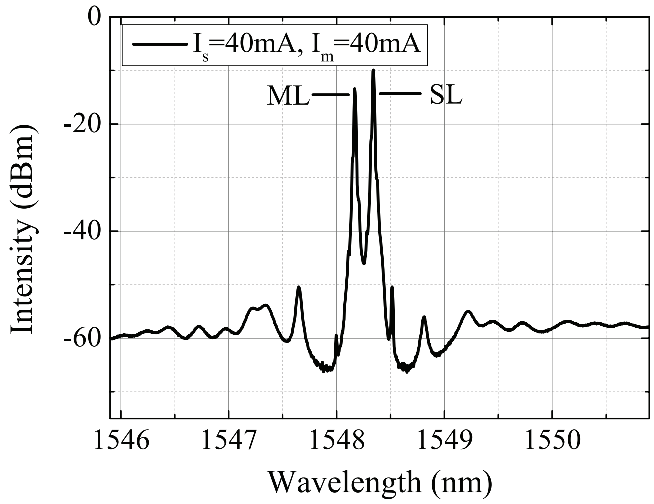

Figure 4. The typical optical spectrum of the two-section laser under condition: $I_s = 40$ mA and $I_m = 40$ mA.

3. Results and discussion

Figure 3 shows the schematic of the experiment setup. The working temperature of the two-section laser is controlled at 20 °C by a thermoelectric cooler (TEC). The ML and SL are biased at I_m and I_s separately by the DC current drivers, and the SL is modulated by a RF signal produced by a microwave frequency synthesizer. The output light of the two-section DFB laser is directed into optical spectrum analyzer via a 50:50 coupler. The other arm of the coupler is used to analyze the beat signals via a high-speed PD and an electrical spectrum analyzer.

3.1. Tunable microwave generation

In the experiment, we firstly investigate the optical spectrum and beat signals of the device without RF signal injecting into SL. Figure 4 shows the typical optical spectrum of the two-section laser under condition: $I_s = 40$ mA and $I_m = 40$ mA. The two peaks are the main modes of ML and SL respectively. The beating of these two peaks can generate microwave signals. Figure 5 shows the variation of wavelengths and power of ML and SL with I_m when I_s is fixed at 50 mA. It can be seen in figure 5(a) that both wavelengths of ML and SL have a red-shift due to the rising temperature induced by the increasing of I_m. Since the temperature of ML rises faster than that of SL with the increase of I_m, the difference between the two wavelengths (blue line) in figure 5(a) decreases. Figure 5(b) shows that the intensity of the SL decreases with the increase of I_m, for the increase of ML's photons induces more consumption of SL's carriers. As shown in figure 6(a), the frequency of the beat signal decreases from 34.2 GHz to 14.9 GHz with the increase of I_m, which corresponds to the difference of the two wavelengths in figure 5(a). The power of the beat signal is proportional to the product of the intensity of the two peaks [21]. Therefore, the power of the beat signals in figure 6(a) is corresponding to the sum of intensity (blue line) in figure 5(b).

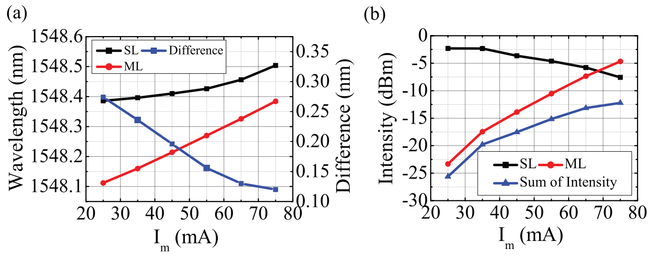

Figure 5. Measured optical wavelength (a) and intensity (b) with I_m varied from 25 to 75 mA and I_s fixed at 50 mA. The blue lines are the difference between the two wavelengths in (a) and the sum of SL's and ML's intensity in (b).

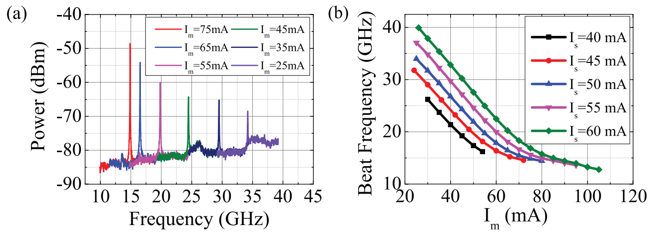

Figure 6. (a) Electrical spectrum of the beat signals when I_s is fixed at 50 mA and I_m varies from 25 mA to 75 mA. (b) The range of the beat frequency when I_s varies from 40 mA to 60 mA.

Figure 6(b) shows the measured relationship between beat frequency and I_m with I_s fixed at different currents. The range of the beat frequency is enlarged when the I_s has a high value. When the SL is biased at 60 mA, the tunable range of the beat frequency is13 GHz to 40 GHz with I_m changed from 26 mA to 105 mA.

3.2. Frequency up-conversion and signal properties enhancement

However, the beat signals appear noisy with relative wide linewidth because the two beat waves are lack of phase correlation. In order to acquire a high-quality signal, a 7.98 GHz RF signal with 3 dBm generated by microwave frequency synthesizer is injected into the SL when the I_s is 50 mA and the I_m is 70 mA. The second sideband of the modulated SL is locked to the ML, which can synchronize the optical phase of ML and SL. Figure 7(a) shows the spectrum of beat signals for the cases of SL with and without RF signal, respectively. Obviously, the beat signal without RF signal has a broader 3 dB linewidth of 23.1 MHz. As a comparison, the zoom-in-view of the locked beat signal shows a 3 dB linewidth of 102 Hz in figure 7(b). Figure 8(a) shows the optical spectrum

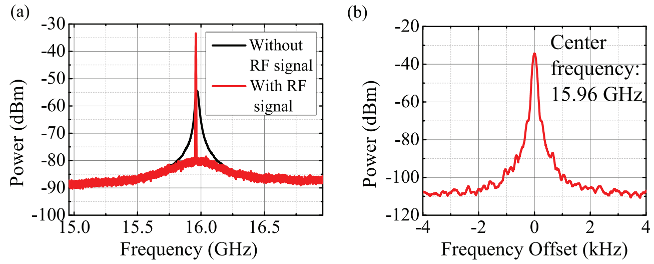

Figure 7. (a) Spectrum of beat signals for the case of SL with and without RF signal. The black line shows the initiate signal without electrical injection; the red line shows the locked signal with RF signal; (b) zoom-in-view of the locked beat signal at 15.96 GHz. The span and RBW are 8 kHz and 100 Hz.

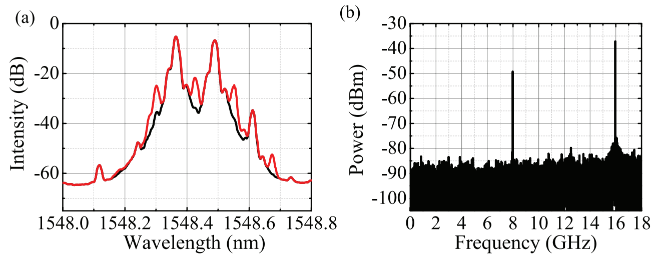

Figure 8. (a) Optical spectrum of the device for case of free-running (black) and frequency-doubled up-conversion (red); (b) electrical spectrum of the beat signal on the condition of frequency-doubled up-conversion.

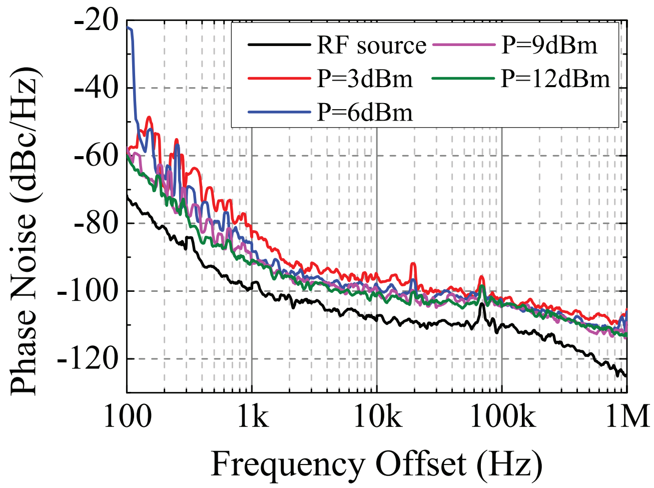

Figure 9. Phase noise of RF source with power of 12 dBm and the beat signals with different RF power.

of the device in free-running and frequency-doubled up-conversion states, respectively. After the injection, a series of sidebands of SL appear, and the main mode of ML locks the +2nd order of the SL's sidebands. Under the injection locking, we obtain a high-quality 15.96 GHz beat signal whose power is 12.02 dB greater than that of the fundamental frequency at 7.98 GHz, as shown in figure 8(b).

Then, we vary the power of injected RF signal and investigate the phase noise of the beat signals. The power of the injected RF signal is increased from 3 dBm to 12 dBm with the frequency fixed at 7.98 GHz. Figure 9 shows the phase

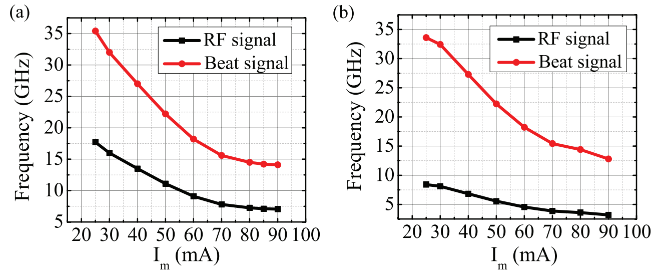

Figure 10. The tuning range of beat signals under frequency-doubled up-conversion (a) and frequency-quadrupled up-conversion (b) when I_s is fixed at 50 mA and I_m varies from 25 mA to 90 mA.

noise of RF source with power of 12 dBm and the beat signals with different injected RF power. The phase noise decreases due to the enhancement of RF power. The phase noise is −100.9 dBc/Hz at 10 kHz frequency offset when the RF signal's power is 12 dBm.

Furthermore, we fix the I_s at 50 mA and vary the I_m from 25 mA to 90 mA to achieve tunable frequency-doubled and frequency-quadrupled signals. The double frequency and quadruple frequency with the frequency of the injected RF signal are described in figure 10 respectively. In the experiment, high RF power is needed to ensure the injection locking when the frequency difference between the SL's main mode and the injected sideband is enlarged. However, as long as the beat frequency is not very high, relative low RF power is enough for frequency up-conversion. For example, when the ML is biased at 50 mA, a 3 dBm RF signal at 5.56 GHz can produce a frequency-quadrupled signal at 22.24 GHz. Therefore, the proposed scheme will be a viable choice when high RF power and frequency are not available.

4. Conclusion

In conclusion, a monolithically integrated two-section DFB laser is fabricated for the tunable and high-quality microwave generation. The DFB lasers for microwave generation are fabricated with equivalent phase shifts and chirps, which can provide good SLM operation and precisely controlled wavelength with low costs. When the wavelengths of the ML and the SL beat in the high-speed PD, a beat signal is generated. The beat frequency can vary from 13 GHz to 40 GHz. If higher beat frequency is needed, it will be easily realized by adjusting the designed wavelengths of the DFB lasers. To enhance the properties of the beat signals, the sideband optical injection locking technique is utilized. The linewidth of the beat signal is narrowed to 102 Hz and the phase noise of the microwave signal is −100.9 dBc/Hz at 10 kHz frequency offset when the injected RF power is 12 dBm, which can be further improved by using a high-quality RF source. Besides, tunable frequency-doubled and frequency-quadrupled signals are achieved respectively, which is useful to generate microwave signals with high frequencies when high RF power and frequency are not available.

Acknowledgments

This work is supported in part by the Chinese National Key Basic Research Special Fund (2017YFA0206401), the National Natural Science Foundation of China (61504058, 61435014, 61504170), the Natural Science Foundation of Jiangsu Province of China (BK20160907), the NUPTSF (NY215041, NY216013, NY217049), the Chinese National Key Basic Research Special Fund (2017YFA0206401), the Jiangsu Science and Technology Project (BE2017003-2), and the Suzhou technological innovation of key industries (SYG201844).

References

[1] Yao J P 2009 Microwave photonics *J. Lightwave Technol.* **27** 314
[2] Fice M J, Rouvalis E, van Dijk F, Accard A, Lelarge F, Renaud C C, Carpintero G and Seeds A J 2012 146-GHz millimeter-wave radio-over-fiber photonic wireless transmission system *Opt. Express* **20** 1769
[3] Diaz R, Chan S C and Liu J M 2006 Lidar detection using a dual-frequency source *Opt. Lett.* **31** 3600
[4] Feiste U, As D J and Ehrhardt A 1994 18 GHz all-optical frequency locking and clock recovery using a self-pulsating two-section DFB-laser *IEEE Photonics Technol. Lett.* **6** 106
[5] Hwang S K, Liu J M and White J K 2004 35-GHz intrinsic bandwidth for direct modulation in 1.3 μm semiconductor lasers subject to strong injection locking *IEEE Photonics Technol. Lett.* **16** 972
[6] Sarailou E, Ardey A and Delfyett P J 2012 Low noise ultra-short pulse generation by direct RF modulation at 22 GHz from an AlGaInAs multiple quantum-well laser at 1.55 μm *IEEE Photonics Technol. Lett.* **24** 1561
[7] Yao X S and Maleki L 1996 Optoelectronic oscillator for photonic systems *IEEE J. Quantum Electron.* **32** 1141
[8] Johansson L A and Seeds A J 2003 Generation and transmission of millimeter-wave data-modulated optical signals using an optical injection phase-lock loop *J. Lightwave Technol.* **21** 511
[9] Simonis G J and Purchase K G 1990 Optical generation, distribution, and control of microwaves using laser heterodyne *IEEE Trans. Microw. Theory Tech.* **38** 667
[10] Goldberg L, Yurek A M, Taylor H F and Weller J F 1985 35 GHz microwave signal generation with an injection-locked laser diode *Electron. Lett.* **21** 814
[11] Sartorius B, Mohrle M and Feiste U 1995 12–64 GHz continuous frequency tuning in self-pulsating 1.55 μm multiquantum-well DFB lasers *IEEE J. Sel. Top. Quantum Electron.* **1** 535
[12] Xinhong W, Weiming M, Al-Mumin M, Pappert S A, Jin H and Guifang L 1999 Optical generation of microwave/millimeter-wave signals using two-section gain-coupled DFB lasers *IEEE Photonics Technol. Lett.* **11** 1292
[13] Laperle C, Svilans M, Poirier M and Tetu M 1999 Frequency multiplication of microwave signals by sideband optical injection locking using a monolithic dual-wavelength DFB laser device *IEEE Trans. Microw. Theory Tech.* **47** 1219
[14] Chien C Y, Lo Y H, Wu Y C, Hsu S C, Tseng H R and Lin C C 2014 Compact photonic integrated chip for tunable microwave generation *IEEE Photonics Technol. Lett.* **26** 490
[15] Hyuk K S, Jung T, Wu M C, Tishinin D, Liou K Y and Tsang W T 2003 Optical generation of millimeter-waves using monolithic sideband injection locking of a two-section DFB laser *The 16th Annual Meeting of the IEEE Lasers and Electro-Optics Society, 2003. LEOS 2003* p 1005
[16] Vieu C, Carcenac F, Pepin A, Chen Y, Mejias M, Lebib A, Manin-Ferlazzo L, Couraud L and Launois H 2000 Electron beam lithography: resolution limits and applications *Appl. Surf. Sci.* **164** 111
[17] Zhang Y *et al* 2017 Modulation properties enhancement in a monolithic integrated two-section DFB laser utilizing side-mode injection locking method *Opt. Express* **25** 27595
[18] Dai Y T and Chen X F 2007 DFB semiconductor lasers based on reconstruction-equivalent-chirp technology *Opt. Express* **15** 2348
[19] Jia-Ming L and Simpson T B 1994 Four-wave mixing and optical modulation in a semiconductor laser *IEEE J. Quantum Electron.* **30** 957
[20] Lo Y H, Wu Y C, Hsu S C, Hwang Y C, Chen B C and Lin C C 2014 Tunable microwave generation of a monolithic dual-wavelength distributed feedback laser *Opt. Express* **22** 13125
[21] Baylón-Fuentes A, Hernández-Nava P, Zaldivar-Huerta I E, Rodríguez-Asomoza J, García-Juárez A and Aguayo-Rodríguez G 2011 Microwave signal generation based on optical heterodyne and its application in optical telecommunication system *CONIELECOMP 2011, 21st Int. Conf. on Electrical Communications and Computers* p 334