Photonic Generation of Microwave Signal Using a Dual-Wavelength Single-Longitudinal-Mode Fiber Ring Laser

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***Abstract*—A novel approach for the generation of high-frequency microwave signals using a dual-wavelength single-longitudinal-mode fiber ring laser is proposed and demonstrated. In the proposed configuration, a dual-wavelength fiber Bragg grating (FBG) with two ultranarrow transmission bands in combination with a regular FBG is used to ensure single-longitudinal-mode operation of the fiber ring laser. A semiconductor optical amplifier is employed as the gain medium in the ring cavity. Since the two lasing wavelengths share the same gain cavity, the relative phase fluctuations between the two wavelengths are low and can be used to generate a low-phase-noise microwave signal without need of a microwave reference source. Three dual-wavelength ultranarrow transmission-band FBGs with wavelength spacing of 0.148, 0.33, and 0.053 nm are respectively incorporated into the laser. Microwave signals at 18.68, 40.95, and 6.95 GHz are obtained by beating the dual wavelengths at a photodetector. The spectral width of the generated microwave signals as small as 80 kHz with a frequency stability better than 1 MHz in the free-running mode at room temperature is obtained.**

***Index Terms*—Fiber ring lasers, homogeneous line broadening, phase-shifted fiber Bragg gratings (FBGs), photonic microwave signal generation, semiconductor optical amplifier (SOA), single longitudinal mode (SLM).**

I. Introduction

OPTICAL generation of microwave and millimeter-wave signals is of great interest for many applications such as broad-band wireless access and sensor networks, software-defined radio, radar, and satellite communication systems. The key advantage of generating microwave or millimeter-wave signals by optical means is that very high-frequency signals with very low phase noise can be generated by beating two optical signals with a wavelength spacing corresponding to the desired microwave or millimeter-wave frequency. In addition, the signals can be distributed over an optical fiber by taking the advantages of the extremely low transmission loss of standard single mode fiber. Furthermore, by incorporating erbium-doped fiber amplifiers (EDFAs) in the transmission link, the signals can be distributed over a very long distance.

In general, photonic generation of microwave or millimeter-wave signals can be divided into three categories. In the first category, two laser beams from two different laser sources are applied to a photodetector (PD). A beat signal with a frequency equivalent to the spacing of the two wavelengths is obtained at the output of the photodetector. To generate a signal with low phase noise and high stability, the phases of the two laser sources must be locked, which are usually implemented by using optical injection locking [1], [2] or by an optical phase-locked loop [3], [4]. For both methods, a high-quality microwave reference signal is required. For many applications, such as wireless communication and radar systems, the microwave generation system would be used as a local oscillator, and no reference source is available.

In the second category, microwave signals are generated based on external modulation technique. The external modulator can be either an electrooptic intensity modulator or a phase modulator. A system that could generate millimeter-wave signals using an external intensity modulator was proposed in 1992 by O'Reilly *et al.* [5]. A frequency-doubled electrical signal was optically generated by biasing the intensity modulator to suppress the optical carrier and the even-order optical sidebands. A 36-GHz millimeter-wave signal was generated when the intensity modulator was driven by an 18-GHz microwave signal. Such a system was employed for remote delivery of video services [6]. Recently, an approach using an external phase modulator to generate a frequency-quadrupled electrical signal was proposed [7]. In the approach, a Fabry–Perot filter was used to select the two second-order optical sidebands. Electrical signal that has four times the frequency of the electrical drive signal was generated by beating the two second-order sidebands at a photodetector. A key advantage of these approaches [5], [7] is that frequency-doubled or -quadrupled signals can be generated with a relatively low-speed external modulator. However, similar to the approaches in the first category, a high-quality microwave reference source is required.

To avoid using a reference microwave source, in the third category, microwave or millimeter-wave signals are generated by using a single laser source. To obtain a beat signal at the output of a photodetector, the laser source should have either a single wavelength with dual longitudinal modes [8] or two wavelengths operating in single longitudinal mode (SLM)

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for each wavelength [9]. The beating of the dual longitudinal modes [8] or the two SLM wavelengths [9] would generate a microwave signal with the required frequency.

Very recently, a dual-wavelength SLM fiber ring laser with a wavelength spacing as small as 0.147 nm was proposed [10] by using an ultranarrow transmission-band (UNTB) dual-wavelength fiber Bragg grating (FBG), fabricated using the equivalent phase shift (EPS) technique [11], [12]. The SLM operation of the fiber ring laser is ensured by the UNTB FBG. To avoid wavelength competition between the two lasing wavelengths at room temperature, a semiconductor optical amplifier (SOA) was used as the gain medium. It is known that semiconductor gain materials have a much weaker homogeneous line-broadening effect compared to erbium-doped fiber (EDF) gain material [13]. In [10], the investigation was focused on the fabrication of a UNTB dual-wavelength FBG and its application in a stable dual-wavelength SLM laser. No effort was made to investigate the generation of microwave signals using the proposed dual-wavelength SLM fiber ring laser. In this paper, a detailed investigation of microwave signal generation using a dual-wavelength SLM fiber ring laser is reported. To generate microwave signals with different frequencies, three UNTB dual-wavelength FBGs with different wavelength spacings are fabricated and incorporated in the fiber ring laser for dual-wavelength SLM operation. It is known that FBGs written in hydrogen-loaded fibers have higher insertion loss compared to those written in nonhydrogen-loaded fibers. To investigate the performance of the proposed fiber laser using hydrogen-loaded and nonhydrogen-loaded FBGs, two of the UNTB dual-wavelength FBGs are fabricated using nonhydrogen-loaded photosensitivity fiber, and one is fabricated using hydrogen-loaded photosensitivity fiber. Better performance is observed when nonhydrogen-loaded photosensitivity fiber is used. Since the laser is based on all fiber-optic components, it can be easily used in fiber-optic systems, such as radio-over-fiber networks. Since the two wavelengths are generated from the same laser cavity, the relative phase fluctuations between the two wavelengths are low. Experimental results show that the spectral width of the generated microwave signals as small as 80 kHz with a frequency stability better than 1 MHz in the free-running mode at room temperature is obtained.

II. Principle

To generate a high-quality microwave signal by beating two wavelengths from a single fiber ring laser, the following issues must be carefully addressed.

1) The two wavelengths must be oscillating in SLM.
2) There is no mode hopping for both wavelengths.
3) The wavelength spacing between the two wavelengths must be stable.
4) The relative phase fluctuation between the two wavelengths must be very small.

The first three issues can be fixed by using the specially designed FBGs using the EPS technique. First, the SLM operation is ensured by using the UNTB FBGs [10]. Second, the use of the UNTB FBGs will also eliminate mode hoping in the two wavelengths. Finally, since the dual wavelengths are generated by using a dual-wavelength UNTB FBG, the relative wavelength spacing is very stable.

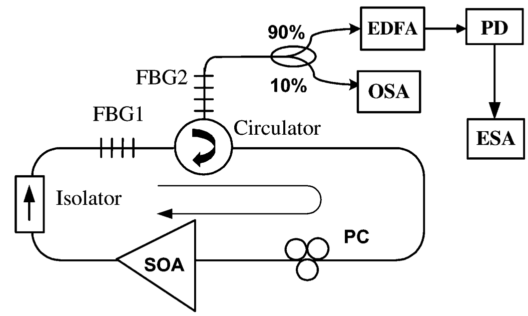

Fig. 1. Schematic diagram of the proposed dual-wavelength SLM fiber ring laser. PC: polarization controller; PD: photodetector; ESA: electrical spectrum analyzer; OSA: optical spectrum analyzer; SOA: semiconductor optical amplifier; EDFA: erbium-doped fiber amplifier.

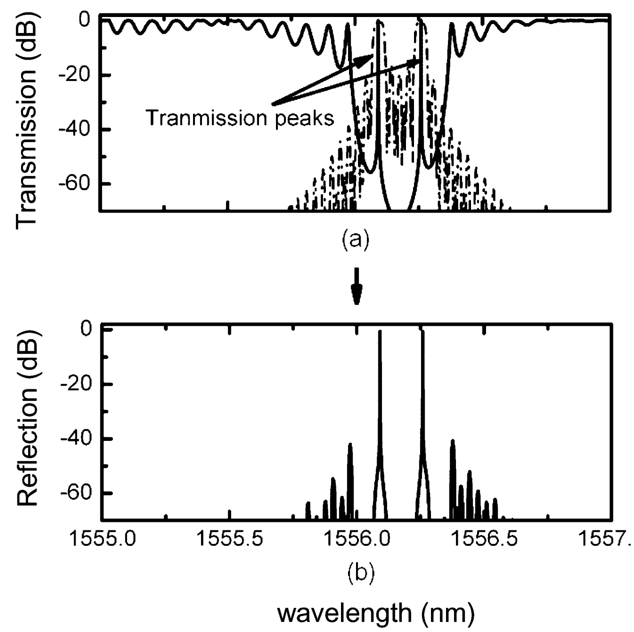

Fig. 2. Schematic optical spectra of FBG1 and FBG2. (a) Optical spectra of FBG1 (solid line) and FBG2 (dotted line). (b) The overall optical spectrum of FBG1 and FBG2 connected via an optical circulator.

In the approaches in [1]–[4], the phases of the two wavelengths from two lasers are locked to a reference source. In our proposed system, the phases of the two wavelengths are not controlled. However, since the two wavelengths are generated by a single phase-shifted UNTB FBG or an FBG consisting of two closely located UNTB FBGs in the same laser cavity, the phase fluctuations due to environmental changes are minimized.

The schematic diagram of the dual-wavelength SLM fiber ring laser employed for microwave generation is shown in Fig. 1. Two FBGs are used in the laser cavity. FBG1 is a UNTB FBG, which is used to restrict the laser's operation in SLM. FBG2 is a regular uniform dual-wavelength reflection FBG, which is used to select the ultranarrow dual-transmission bands of FBG1. Fig. 2(a) is the schematic diagram of the optical spectra of FBG1 (solid line) and FBG2 (dashed–dotted line). The two transmission bands of FBG1 fall within the two

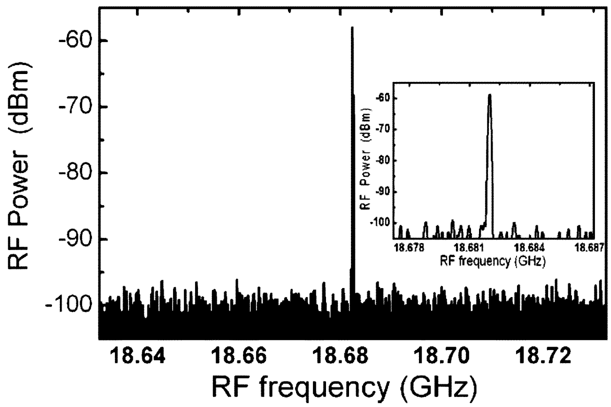

Fig. 3. Electrical spectrum of the beat signal observed at the output of the photodetector. The insert shows the detail of the RF signal with a span of 10 MHz.

refection bands of FBG2. By combining the two FBGs with an optical circulator, an overall transmission spectrum with two ultranarrow transmission bands shown in Fig. 2(b) is obtained. In the experiment, FBG2 is tuned in order to have a good match between the reflection bands of FBG2 and the transmission bands of FBG1. FBG2 is also finely tuned to balance the output optical power of the two lasing wavelengths.

In our experiments, three sets of the FBGs are fabricated to produce 18.68-, 40.95-, and 6.95-GHz microwave signals. To avoid strong homogeneous line broadening of the EDF at room temperature, in the laser cavity we use an SOA as the gain medium. The SOA is made by JDS-U (model: CQF9 721 108-C) with a maximum gain of 23 dB. A polarization controller (PC) is used before the SOA to align the polarization direction of the light entering the SOA. In addition, an isolator is used to block the reflection light from FBG1 into the SOA. The lasing output is obtained from the other end of FBG2. The output power is split into two parts by a 90 : 10 optical coupler. Ten percent of the optical power is sent to an optical spectrum analyzer (OSA), and 90% of the output power after amplification by an EDFA is applied to the photodetector. The beat signal at the output of the photodetector is observed by an electrical spectrum analyzer.

III. Experiment

Three dual-wavelength UNTB FBGs (FBG1-1, FBG1-2, FBG1-3) with wavelength spacings of 0.148, 0.33, and 0.053 nm are fabricated. First, we experiment with FBG1-1 by incorporating it into the fiber ring cavity. FBG1-1 is fabricated using the equivalent phase-shift technique by introducing two EPSs during the fabrication process [10], [11]. The basic structure of FBG1-1 and the performance of the dual-wavelength SLM fiber ring laser have been discussed in [10]. It should be mentioned that simultaneous lasing of the two wavelengths requires a careful balance of the polarization state within the ring cavity and the net gain of the two wavelengths. When the driving current of the SOA is 145 mA, a stable dual-wavelength laser is obtained.

By applying the lasing output to a photodetector, a beat signal is observed. Fig. 3 shows the electrical spectrum of the generated microwave signal. The inset in Fig. 3 shows the details of the microwave signal with a span of 10 MHz. The microwave frequency is 18.68 GHz, corresponding to the wavelength spacing of the dual wavelengths of 0.148 nm. We should note that the dual-wavelength lasing is really operating in SLM. This is verified by observing the spectrum of the beat signal. As can be seen from Fig. 3, only a microwave signal generated by beating of the two wavelengths is observed. No beat signals at frequencies equal to the round-trip frequency of the fiber ring laser and its multiples are observed. For the beat signal at 18.68 GHz, the short-time ($<h$) frequency drift is less than 2 MHz and its spectral width is less than 200 kHz when the laser is operating in the free-running mode at room temperature.

For phase-shifted FBGs with two transmission bands, the two transmission peaks must be fallen within the stopband. The beating frequency, which is determined by the wavelength spacing between the two narrow transmission peaks, will be smaller than the bandwidth of the stopband. The maximum index modulation of an FBG determines the bandwidth of the stopband. For FBGs fabricated using the equivalent phase-shift technique with wavelength spacing corresponding to a frequency higher than 40 GHz, the maximum index modulation should be larger than 1.5×10^{-3}, which is difficult for conventional photosensitivity fiber.

To generate microwave signals with frequencies higher than 40 GHz, a second FBG (FBG1-2) is fabricated. FBG1-2 consists of two cascaded 24.4-mm-long phase-shifted FBGs which are separated by 1 mm along the fiber. The phase shift in each FBG of FBG1-2 is induced directly in a conventional FBG by leaving a segment of fiber without UV exposure. We called this type of "equivalent phase shift" EPS-II in this paper, while the EPS in [10] and [11] is called EPS-I. Fig. 4 shows the schematic diagram of FBG1-2. Assuming that the difference of the average index between the parts with grating structure and without grating structure is δn_b, and the length of the nonexposure part is δl_b, the phase shift ϕ_{ps} is then equal to

$$\phi\mathrm{ps} = \frac{n_0 \delta n_b \delta l_b}{\lambda} \tag{1}$$

where n_0 is the average refractive index of the fiber grating. EPS-II has the same quality as EPS-I but it is a little more difficult to control during the fabrication, since both δn_b and δl_b are difficult to measure and control precisely. In addition, the EPS-II technique is not suitable for producing many EPSs in an FBG. Since the EPS-II needs smaller refractive index modulation, we can use the conventional photosensitivity fiber without hydrogen loading. As we will show later, it is advantageous to use nonhydrogen-loaded FBG.

The two FBGs in FBG1-2 are cascaded along the fiber with 1-mm spacing, and each FBG has one EPS-II in the center of the grating. Same as FBG1-1, FBG1-2 is fabricated using a frequency-doubled ion laser operating at 244 nm with an output power of 100 mW. During the fabrication, when the laser is scanning near the center of the FBG, a shutter which blocks the UV beam is closed, which leads to about 1.1 mm of the fiber without UV exposure (the full-width at half-maximum (FWHM) of the UV beam along the fiber is about 0.7 mm). The averaged index modulation of the FBG is about 1.8×10^{-4}.

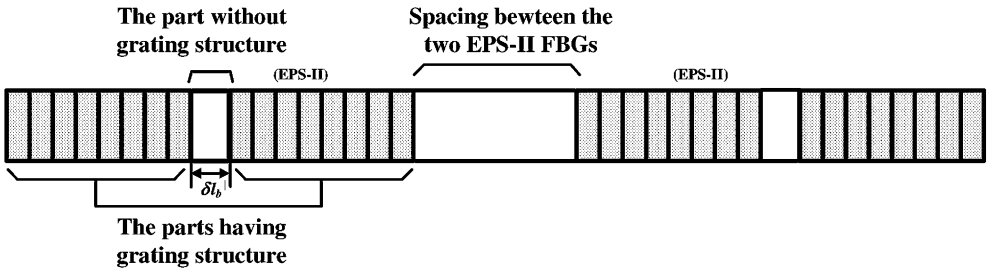

Fig. 4. Schematic diagram of FBG1-2. It consists of two cascaded EPS-II FBG's with an EPS introduced by a nonexposure part at the center of each FBG.

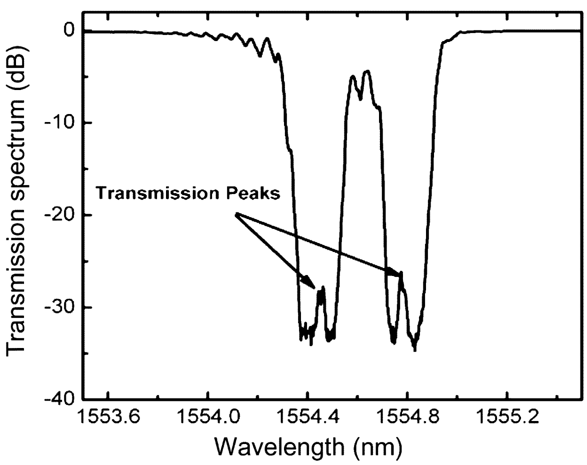

Fig. 5. Measured transmission spectrum of FBG1-2.

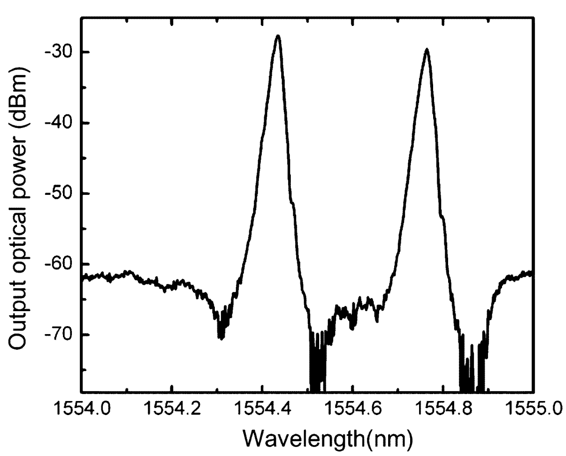

Fig. 6. Optical spectrum of the lasing output when FBG1-2 is used.

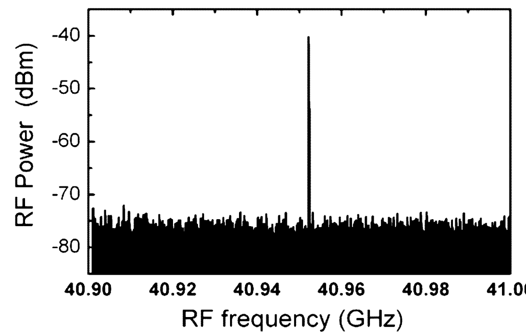

Fig. 7. Electrical spectrum of the beat signal observed at the output of the photodetector when FBG1-2 is used.

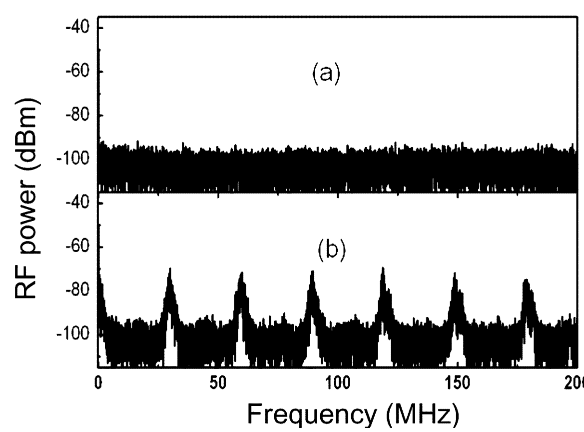

Fig. 8. Electrical spectrum of the beat signals. (a) SLM operation. (b) Multiple-longitudinal-mode operation.

The wavelength spacing between the two transmission bands is 0.33 nm, as shown in Fig. 5, which corresponds to a beating frequency of 40.95 GHz.

By incorporating FBG1-2 into the ring cavity, a dual-wavelength lasing with a wider wavelength spacing is observed. The optical spectrum of the lasing output is shown in Fig. 6. The beat signal is then obtained at the output of the photodetector. The electrical spectrum of the beat signal is shown in Fig. 7. To obtain a dual-wavelength lasing, the injection current to the SOA is adjusted to be 137 mA. To further verify if the dual-wavelength lasing is operating in SLM, we display the electrical spectrum from 0 to 200 MHz on an electrical spectrum analyzer. It can be seen from Fig. 8(a) that no beat signal between the multiple longitudinal modes is observed, which demonstrates that the laser is operating in SLM. When FBG2 is tuned to have the two reflection bands outside the stopband of FBG1-2, the overall transmission bands of FBG2 and FBG1-2 are only determined by FBG2. Since FBG2 is a regular reflection FBG with large reflection bandwidth, the laser is no longer operating in SLM, and beat signals between the multiple longitudinal modes are observed, as shown in Fig. 8(b). The frequency spacing between the neighboring beat signals is 30 MHz, which corresponds to a cavity length of about 6.8 m.

The spectral width of the generated microwave signal in the free-running mode is measured to be less than 300 kHz. The frequency drift is less than 2 MHz. Compared with the experiment using FBG1-1, the use of FBG1-2 leads to an increased sensitivity to polarization, which affects both the output power and the spectral width of the generated microwave signal. The reason for this phenomenon may be explained by the fact that FBG1-1 is a single FBG with two transmission bands, while

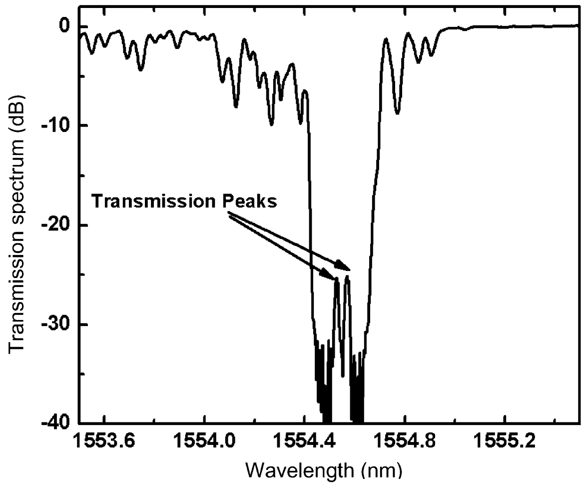

Fig. 9. Measured transmission spectrum of FBG1-3.

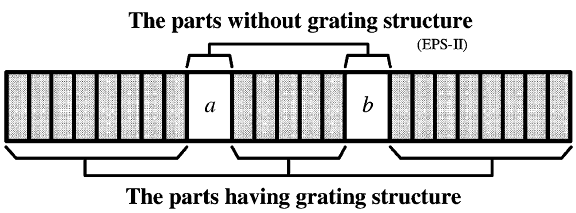

Fig. 10. Schematic diagram of FBG1-3. It consists of two EPSs (EPS-II) in a single FBG introduced by two nonexposure parts at positions a and b. The distance between a and b is 2.2 mm.

FBG1-2 is actually two independent FBGs cascaded in a fiber. The polarization states of the two cascaded FBGs may be different, which will affect the output power and the spectral width of the generated microwave signal.

It is known that fibers with hydrogen loading would have a higher insertion loss than nonhydrogen-loaded fibers. For phase-shifted FBGs, since the transmission bands are ultranarrow, the loss induced by the hydrogen loading become more serious. FBG1-1 is an EPS-I FBG with two ultranarrow transmission bands but is fabricated in a hydrogen-loaded photosensitivity fiber, while FBG1-2 is fabricated in a nonhydrogen-loaded photosensitive fiber but actually has two separated EPS-II FBGs. The third FBG (FBG1-3) to be tested is a single FBG with two EPS-II-type EPSs fabricated in nonhydrogen-loaded photosensitive fiber. Fig. 9 shows the transmission spectrum of FBG1-3: two ultranarrow transmission bands are observed. The total length of FBG1-3 is 25 mm. The two EPSs are introduced by two segments of fiber of 1.1 mm in length without UV exposure, as shown in Fig. 10. The two nonexposed fiber segments are separated by 2.2 mm. By incorporating FBG1-3 into the fiber ring laser, a very stable dual-wavelength lasing is obtained. The spectrum of the laser output is shown in Fig. 11. The wavelength spacing between the two wavelengths is 0.053 nm, corresponding to a beat frequency of 6.63 GHz.

A microwave signal is then obtained by beating the two wavelengths at the photodetector. The electrical spectrum of the beat signal is shown in Fig. 12. To study its stability, four measurements are taken at a time interval of 15 min. The microwave

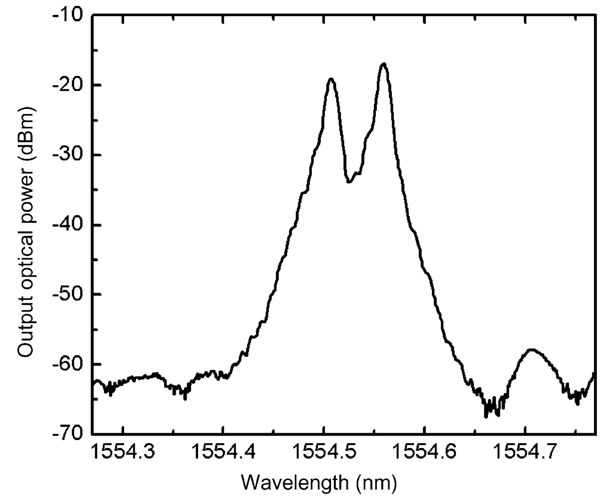

Fig. 11. Optical spectrum of the lasing output when FBG1-3 is used.

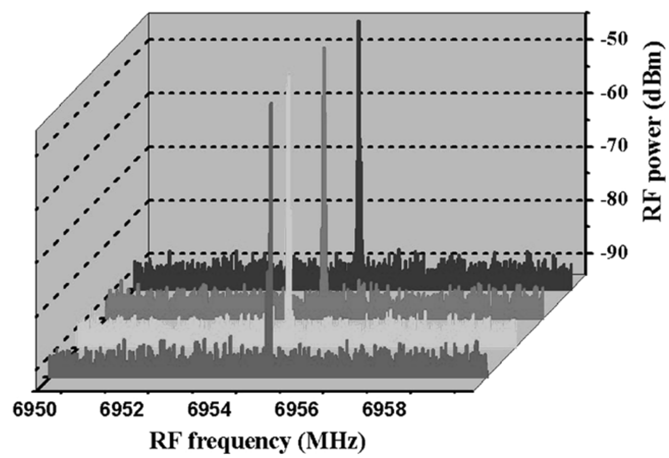

Fig. 12. Electrical spectra of the beat signal at the output of the photodetector when FBG1-3 is used. Four measurements are taken at a 15-min interval without any PC adjustment.

frequencies for the four measurements are 6954.21, 6954.37, 6954.46, and 6954.53 MHz. The spectrum width of the generated microwave signals is less than 80 kHz in the free-running mode at room temperature, which is much smaller than the spectral width when FBG1-1 fabricated in hydrogen-loaded photosensitive fiber is used. A frequency drift that is less than 1 MHz is observed. During the experiment, the PC is not adjusted to compensate for the polarization change of the cavity. It is known that a polarization change in the cavity would lead to a change of the gain and output power of the dual wavelengths, which in turn leads to the power variation of the generated microwave signal. It is shown that the use of an UNTB FBG fabricated in nonhydrogen-loaded photosensitive fiber would provide better performance in terms of output stability and spectral width.

IV. Discussions and Conclusion

Photonic generation of high-frequency microwave signal using a dual-wavelength SLM fiber ring laser has been demonstrated. The key device in the proposed system was the UNTB FBG. By incorporating a UNTB FBG into the fiber ring, dual-wavelength SLM lasing was realized. In our experiment, three UNTB FBGs were fabricated. The first FBG was fabricated in hydrogen-loaded photosensitive fiber by introducing two EPS-I-type EPSs to the FBG during the fabrication process; two ultranarrow transmission bands were obtained. The wavelength spacing of the two transmission bands was 0.148 nm, corresponding to a beat frequency of 18.68 GHz. The second FBG was fabricated in nonhydrogen-loaded photosensitive fiber using EPS-II technique. It was actually composed of two cascaded EPS-II FBGs. Each of them had one ultranarrow transmission band. The wavelength spacing of the two transmission bands was 0.33 nm, corresponding to a beat frequency of 40.95 GHz. The third FBG was also fabricated using EPS-II technique, but was written in nonhydrogen-loaded photosensitive fiber. The wavelength spacing of the two transmission bands was 0.053 nm, corresponding to a beat frequency of 6.63 GHz. The results showed that the performance of the fiber laser using the third FBG was better that that of the first and second FBGs in terms of output stability and generated microwave spectral width.

In a simple structure without any loop control, the spectral width of the generated microwave was as small as 80 kHz, and the frequency drift was as small as 1 MHz. Compared with the microwave signal generated by dual-wavelength SLM semiconductor lasers in the free-running mode [1], the linewidth is decreased (from about 11 MHz to less than 80 kHz), and the frequency stability is also improved.

The proposed system has presented a simple and cost-effective solution to generate high-quality high-frequency microwave signals. The performance can be further improved if the system is properly packaged with temperature control.

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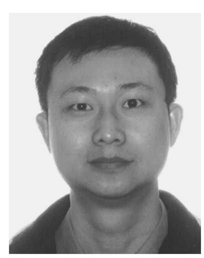

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