Photonic-assisted microwave frequency multiplication with a tunable multiplication factor

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Photonic-assisted microwave frequency multiplication with a tunable multiplication factor (MF) based on an optical comb generator and an embedded single-passband microwave photonic filter (MPF) is proposed and demonstrated. The optical comb is generated using two cascaded modulators which are driven by a microwave reference signal. By applying the optical comb to a photodetector, a fundamental frequency corresponding to the comb spacing and its harmonics is generated. Thanks to the embedded single-passband MPF, only one harmonic is selected by the single-passband MPF. Thus, a single-frequency frequency-multiplied microwave signal is generated. In the proposed system, the embedded single-passband MPF is formed by using a sliced broadband optical source and a section of dispersion-compensating fiber (DCF). By tuning the central frequency of the passband at a frequency corresponding to that of a specific harmonic, a microwave signal at that specific frequency is generated. The proposed system is experimentally demonstrated. A frequency-multiplied microwave signal with an MF from 1 to 5 is generated. The phase noise and frequency tunability of the generated microwave signal are also investigated.

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Photonic generation of microwave signals has been a topic of interest in the last three decades and can find numerous applications, such as wireless access networks, radar, microwave imaging, and modern instrumentation [1,2]. Basically, to photonically generate a microwave signal, two phase-correlated optical waves with a wavelength spacing corresponding to the frequency of the microwave signal to be generated are needed, and the microwave signal is generated by beating the two optical waves at a photodetector (PD). Numerous approaches have been proposed to generate two phase-correlated optical waves, such as the use of two phase-locked laser sources (LSs) through an optical phase-locked loop [3] or optical injection locking of two slave LSs [4]. Two phase-correlated optical waves can also be generated based on external modulation. In [5], a frequency-doubled microwave signal is generated using a single Mach–Zehnder modulator (MZM) that is biased at the minimum transmission point to eliminate all the even-order sidebands. The beating of the ±1st-order sidebands at a PD would generate a frequency-doubled microwave signal. On the other hand, when the MZM is biased at the maximum transmission point, all odd-order sidebands are suppressed. By using a Mach–Zehnder interferometer (MZI) to select only the two ±2nd-order sidebands [6] or simply an optical notch filter, such as a fiber Bragg grating (FBG) [7], to remove the optical carrier, a frequency-quadrupled microwave signal is generated. To eliminate the use of an optical filter, which may limit the tunability of the generation system, a microwave frequency multiplication system using two cascaded MZMs in addition to an electrical phase shifter (EPS) can also be implemented. The phase shifter is used to introduce a phase shift between the two microwave signals to drive the two MZMs [8]. Moreover, microwave frequency multiplication can be realized based on optical nonlinear effects, such as stimulated Brillouin scattering (SBS) [9] and four-wave mixing (FWM) [10,11].

In general, it is expected that the multiplication factor (MF) is large and tunable. Several methods have been reported to implement a microwave frequency multiplication system with a large MF. For example, a photonic-assisted frequency multiplication system with an MF of 6 was demonstrated by using a polarization modulator to generate even-order sidebands, and an FBG to remove the ±1st-order sidebands [12]. A frequency-twelvetupled system was also proposed, which was implemented through a joint operation of polarization modulation, FWM, and SBS-assisted filtering [13]. Recently, we have proposed a photonic approach to generating a microwave signal with a tunable and large MF based on time-delayed optical combs [14]. The beating of the optical comb lines at a PD will generate a fundamental signal and its harmonics, and a tunable multitap microwave photonic filter (MPF) is used to select the desired harmonic. The number of taps is determined by the number of LSs used. To have a narrow passband, the number of taps must be large, which would make the system complicated and costly. In addition, to select the desired harmonic while suppressing all the other harmonics, the wavelengths of the LSs should be precisely calculated and set, since a multitap MPF has multiple passbands, which would again increase the complexity of the system. In addition, due to the multiple passbands, it is hard to completely suppress all other harmonics.

In this Letter, we propose and experimentally demonstrate an approach to implementing microwave frequency multiplication with a tunable MF using an optical comb generator (OCG) and an embedded single-passband MPF. Since the MPF has a single passband, the selection of only a single harmonic with a tunable MF is ensured. The optical comb is generated using two cascaded modulators which are driven by a microwave reference signal. By applying the optical comb to a PD, a fundamental frequency corresponding to the comb spacing and its harmonics are generated. By tuning the central frequency of the passband of the embedded single-passband MPF at the frequency of one harmonic, this harmonic is selected and the other harmonics are suppressed. In the proposed system, the embedded single-passband MPF is realized using a sliced broadband optical source (SBOS) and a section of dispersion-compensating fiber (DCF) [15,16]. A proof-of-concept experiment is carried out. A microwave signal with an MF from 1 to 5 is generated. The phase noise of the generated microwave signal and the frequency tunability are also investigated.

The schematic diagram of the proposed microwave frequency multiplication system is shown in Fig. 1. It consists of an OCG and an embedded single-passband MPF. The OCG mainly includes an MZM and a phase modulator (PM) [17,18], which are driven by a microwave reference signal with one channel being phase shifted by an EPS. The bandwidths of the modulators are 10 GHz. The embedded single-passband MPF is realized using a broadband amplified spontaneous emission (ASE) light source and a section of DCF. As can be seen, the output from the ASE light source is sliced by an MZI. The free spectral range (FSR) of the MZI can be changed by controlling the time delay through tuning the variable optical delay line (VODL) with a tunable range of 660 ps in the upper arm. A tunable optical attenuator (TOA) and a polarization controller (PC1) are incorporated in the lower arm to make the interference pattern have a high extinction ratio. In the experiment, the MZI is placed on an optical table with no special stability control. For practical applications, the MZI should be well packaged to avoid environmental disturbance. The SBOS is then modulated by the microwave reference signal and sent to the DCF through an erbium-doped fiber amplifier (EDFA). The overall function is equivalent to a single-passband MPF with the central frequency tunable by adjusting the VODL. More details about the operation of the single-passband MPF can be found from [15,16]. The joint operation of the single-passband MPF and the OCG would generate a frequency-multiplied microwave signal with the MF tunable by changing the central frequency of the single-passband MPF.

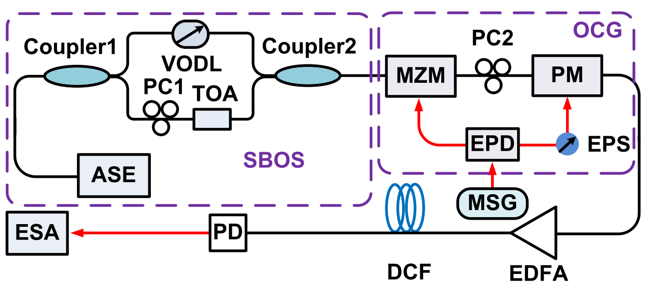

Fig. 1. Schematic diagram of the proposed photonic-assisted microwave frequency multiplication system. ASE, amplified spontaneous emission; PC, polarization controller; TOA, tunable optical attenuator; VODL, variable optical delay line; SBOS, sliced broadband optical source; MZM, Mach–Zehnder modulator; PM, phase modulator; OCG, optical comb generator; MSG, microwave signal generator; EPS, electrical phase shifter; EPD, electrical power divider; EDFA, erbium-doped fiber amplifier; DCF, dispersion compensating fiber; PD, photodetector; ESA, electrical spectrum analyser.

The ASE source is sliced by the MZI, which has a sinusoidal spectral response. It has been proved mathematically that the joint operation of an SBOS with a sinusoidal spectral response and a dispersive element will realize an MPF with only a single passband [15,16]. The central frequency of the single-passband MPF is expressed as

$$f_p = \frac{1}{\chi \Delta\lambda}, \tag{1}$$

where χ is the total dispersion of the dispersive element and $\Delta\lambda$ is the FSR of the MZI, which can be changed by tuning the VODL.

By tuning the VODL to make the central frequency of the passband located at the frequency of one harmonic, such a harmonic is selected, as shown in Fig. 2.

A proof-of-concept experiment is carried out based on the configuration shown in Fig. 1. Figure 3 shows the sliced spectrum at the output of the MZI. A maximum extinction ratio of 13 dB is obtained by tuning PC1 and the TOA. The channel spacing of the spectrum of the sliced ASE source is adjustable by tuning the VODL.

First, the frequency response of the MPF is measured. To do so, we use a vector network analyzer (VNA, Agilent E8364A) by connecting the output port of the VNA to the

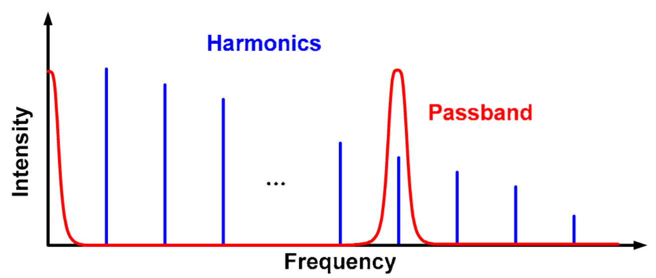

Fig. 2. Principal of the photonic-assisted microwave frequency multiplication.

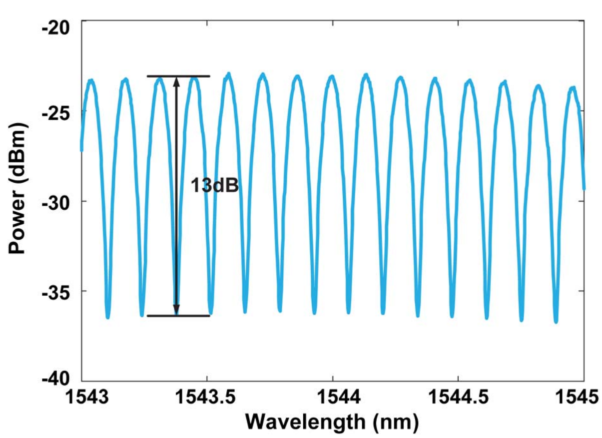

Fig. 3. Optical power spectrum of the SBOS.

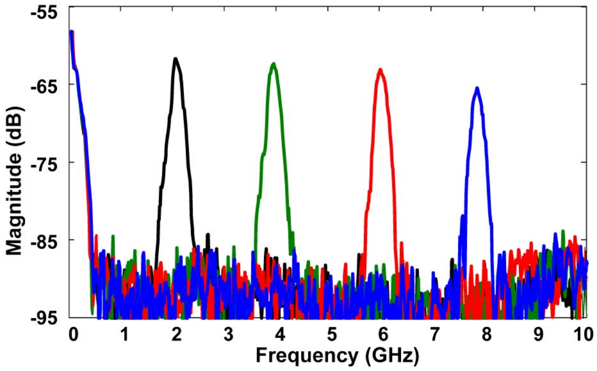

Fig. 4. Frequency response of the MPF. The central frequency of the passband is tuned from 2 to 8 GHz.

input of the OCG and the input port to the output of the PD (New Focus, 3 dB bandwidth of 25 GHz and responsivity of 0.6 A/W). The measured frequency response is shown in Fig. 4. As can be seen, it has a single passband plus a baseband at the DC. The 3 dB bandwidth of the passband is measured to be about 190 MHz. Note that the baseband at the DC has no impact on the signal generation, since the frequency of the microwave reference signal will be far away from the baseband. The tuning of the single-passband MWP is also shown in Fig. 4. As can be seen the central frequency is largely tunable.

Then the generation of an optical comb and the beating of the comb lines to generate a fundamental and its harmonics are studied. To do so, the DCF is removed from the system. Thus, no single-passband MWP exists and all harmonics will be shown at the output of the PD. In the experiment, a microwave reference signal from a microwave signal generator (MSG, Agilent E8254A) at 6 GHz is applied to the OCG. An EPS (HP 87304C) is employed to introduce a phase shift. Multiple harmonics are generated at the output of the PD, which are measured by an electrical spectrum analyser (ESA, Agilent E4448A), as shown in Fig. 5(a).

If the DCF is incorporated into the system, a single-passband MPF is realized. By adjusting the VODL, the central frequency of the passband is tuned. When it is tuned at the frequency of a specific harmonic, this harmonic is selected. Figures 5(b)–5(f) show the spectra of the generated frequency-multiplied microwave signal with different MFs from 1 to 5. As can be seen, only one harmonic is generated by locating the passband of the MPF at the frequency of the harmonic. A zoom-in view of the spectrum for each MF is also given. Compared with the results in [7–14], better suppression is achieved, since no other harmonic can be seen. Note that although the frequency of the modulation signal applied to the OCG should be lower than 10 GHz due to the limited bandwidths of the modulators, the harmonics generated by the OCG could be higher than 10 GHz. In addition, the central frequency of the passband of the MPF is determined by the total dispersion of the dispersive element and the FSR of the MZI. Therefore, the MPF can have a passband with a central frequency also higher than 10 GHz.

The MF in the experiment is from 1 to 5, which can be much greater if the OCG is improved with a flatter comb

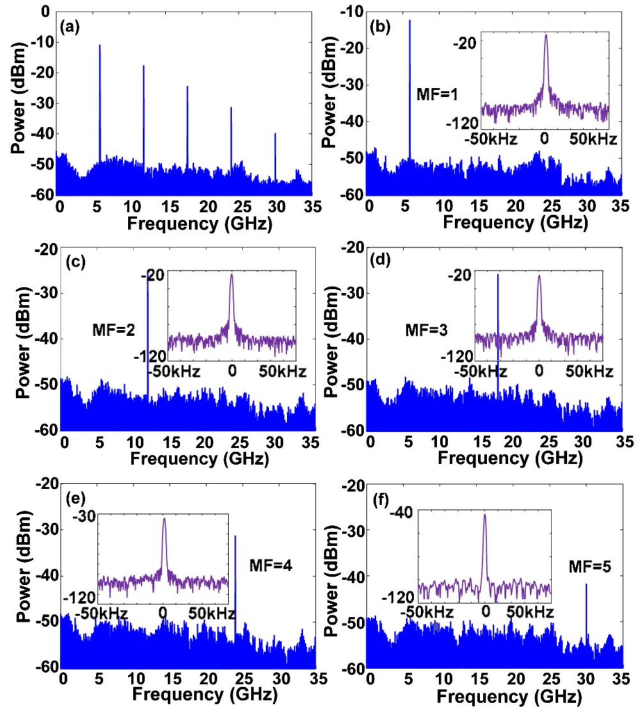

Fig. 5. (a) Generated harmonics when the DCF is not incorporated in the system. (b)–(f) Generated frequency-multiplied signals with an MF tunable from 1 to 5. The resolution bandwidth (RBW) and video bandwidth (VBW) are both 3 MHz for the main figures. The RBW and VBW are both 910 Hz for the insets.

profile and more comb lines. For example, the flatness of a comb and the number of the comb lines can be increased by using modulators with lower half-wave voltages [17], employing more modulators [18], or basing the setup on dual-sine-wave phase-only modulation [19].

The phase noise performance of the generated frequency-multiplied microwave signals with different MFs are investigated. A microwave source analyzer (Agilent E5252B) and a microwave downconverter (Agilent E5053A) are used, and the measured phase noises are shown in Fig. 6. The overall phase noise of a generated signal is determined by the residual phase noise of the system and the phase noise of the reference microwave source. In addition, the multiplication operation will also contribute to an additional phase noise, given by

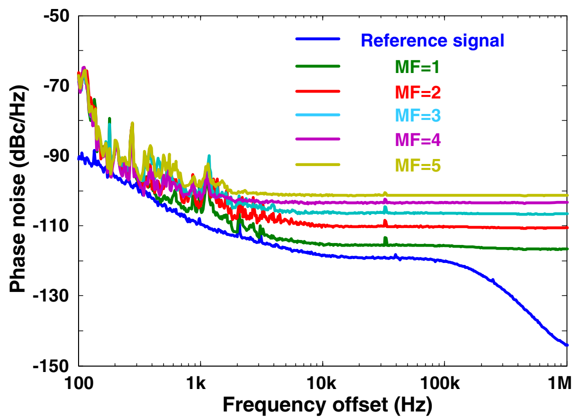

Fig. 6. Phase noise of the generated frequency-multiplied microwave signals.

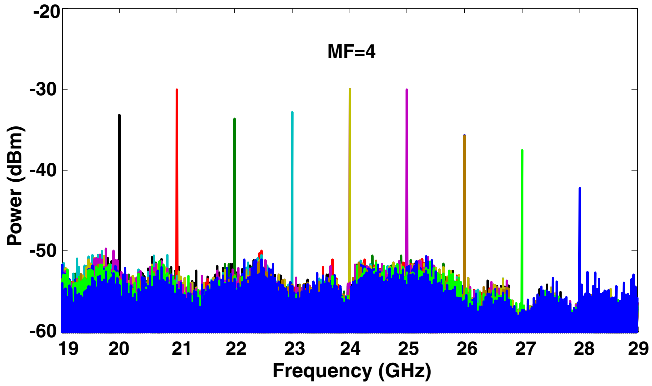

Fig. 7. Frequency tunability of the generated microwave signal for an MF of 4.

$20\log_{10}(\mathrm{MF})$ [20]. As a comparison, the phase noise of the microwave reference signal is also shown in Fig. 6. As can be seen, the phase noise of the generated microwave signal for an MF of 1 is poorer than that of the microwave reference signal, which is mainly due to the noise from the ASE source. The phase noise of the generated microwave signal with a higher MF is increased, which is in accordance with the theoretical calculation by $20\log_{10}(\mathrm{MF})$ [20].

To show the frequency tunability of the proposed system, the frequency of the generated microwave signal is changed by tuning the frequency of the microwave reference source. In the experiment, we fix the MF at 4, and the frequency of the microwave reference source is tuned from 5 to 7 GHz; thus a frequency-multiplied microwave signal from 20 to 28 GHz is generated, as shown in Fig. 7. Note that during the tuning, the central frequency of the passband of the MPF should also be tuned from 20 to 28 GHz accordingly. The fluctuation of the power is mainly caused by the dispersion-induced carrier suppression effect [21] and the frequency response of the PD.

In conclusion, an approach to implementing microwave frequency multiplication with a tunable MF using an OCG and an embedded single-passband MPF was proposed and experimentally demonstrated. The key contribution of the work was the incorporation of a single-passband MPF, which was used to select one harmonic generated by the OCG. Since the central frequency of the passband of the MPF could be continuously tunable, the generation of a frequency-multiplied microwave signal with a tunable MF could be implemented. The MF tuning was implemented by tuning the VODL. It was much simpler and more flexible than the MF tuning in [14], where precise control of the wavelengths was required. In addition, due to the single and narrow passband of the MPF in this scheme, the suppression of other harmonics could be better than those in [7–14]. The proposed system was verified by an experiment. A frequency-multiplied microwave signal with an MF from 1 to 5 was generated. The phase noise and frequency tunability of the generated microwave signal were also investigated.

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