Frequency-Tunable Microwave Generation Based on Time-Delayed Optical Combs

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***Abstract*—A novel approach to generating a frequency-tunable microwave signal based on time-delayed optical combs is proposed and demonstrated. The fundamental principle is to generate multiple optical combs with identical comb profile, but with each optical comb carried by an optical carrier at a different wavelength. If the optical carriers are spaced with an identical wavelength spacing, the optical combs will be time delayed with an identical time delay after passing through a dispersive fiber. By applying these optical combs to a photodetector, microwave comb lines at the fundamental-order and higher order harmonic frequencies will be generated. For a well-designed time-delay structure, however, the desired microwave harmonic will have the highest output due to constructive interference, while the other harmonics will be suppressed. An analysis is performed, which is verified by a proof-of-concept experiment. A microwave signal that is tunable from 16.8 to 27 GHz is generated. The performance of the generated signal in terms of stability and phase noise is also evaluated.**

***Index Terms*—Microwave generation, microwave photonics, optical comb, terahertz generation.**

I. Introduction

PHOTONIC microwave generation has several advantages over conventional electronic techniques [1], [2], such as high frequency and wide frequency tunability. In addition, due to the extremely low loss of the state-of-the-art fibers, a microwave signal can be distributed over an optical fiber over a long distance, which can find applications such as antenna remoting and broadband wireless access.

Numerous techniques for generating microwave signals by optical means have been reported. Typically, the schemes are implemented to ultimately producing two optical waves of different wavelengths, and a microwave is generated by beating the two optical waves at a photodetector (PD). These include utilizing two different light sources [3], employing nonlinear devices [4], and utilizing external optical modulation [5]. It is known that utilizing two independent light sources will produce a microwave signal with a high phase noise. Several proposals were reported to solve this problem, including employing a dual-wavelength single-longitudinal-mode laser source and two phase-locked laser sources through an optical phase-locked loop [6] or through optical injection locking [7]. However, these approaches are expensive and complicated [1]. Optical nonlinear process, on the other hand, could also be utilized to generate high quality microwave signals. For example, microwave generation based on four-wave-mixing (FWM) utilizing a highly nonlinear fiber [4] or a semiconductor optical amplifier (SOA) [8] was proposed. Nonetheless, the associated ultra-low conversion efficiency imposes a severe limitation.

Alternatively, external optical modulation is a promising solution for generating high-quality microwave signals, due to the high performance in terms of tunability, stability, and simplicity. However, the achieved multiplication factor, defined as the ratio between the generated and the input microwave frequencies, is limited. For instance, a frequency octupling (a multiplication factor of 8) was achieved based on two cascaded Mach–Zehnder modulators (MZMs) [9]. Furthermore, a multiplication factor of 12 was recently reported based on a joint operation of polarization modulation, four-wave mixing, and stimulated-Brillouin-scattering-assisted filtering [10]. On the other hand, a much greater multiplication factor could be achieved utilizing an optical comb [11]–[13], in which two narrowband optical filters were utilized to select two of the optical comb lines. The multiplication factor can be as large as 50, only limited by the bandwidth of the PD. The major limitation of this approach is that the two optical filters must be extremely stable with an ultra-narrow bandwidth to ensure a correct wavelength selection, which would make the system very complicated and costly. In addition, the tuning of the microwave frequency is achieved by tuning of the optical filters, which again increases the system complexity and cost.

In this paper, we propose a novel approach to generating a microwave signal utilizing time-delayed optical combs without using optical or microwave filters. The proposed approach is frequency tunable, and can potentially achieve a very large multiplication factor. The fundamental principle is to generate multiple optical combs with an identical comb profile, but each optical comb is carried by an optical carrier at a different wavelength. If the optical carriers are spaced with an identical wavelength spacing, the optical combs will be time delayed after passing through a dispersive fiber, with each microwave comb copy at the output of the PD having different phase shift. Consequently, the microwave-comb copies will interfere. For a well-designed time-delay structure, the desired microwave harmonic will have the highest output due to constructive interference while the other harmonics will be suppressed. An analysis is performed, which is verified by a proof-of-concept experiment.

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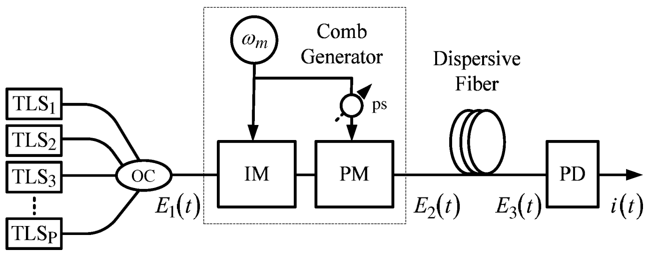

Fig. 1. Structure for microwave or terahertz-wave generation based on time-delayed optical combs. Tunable laser source: TLS. Optical coupler: OC. Intensity modulator: IM. Phase modulator: PM. Photodetector: PD. RF phase shifter: PS.

A microwave signal that is tunable from 16.8 to 27 GHz is generated. The performance of the generated signal in terms of stability and phase noise is also evaluated. The frequency of the generated microwave signal can be extended to the sub-terahertz range by simply utilizing a faster PD.

This paper is organized as follows. In Section II, a theoretical analysis is presented. The generation of a microwave signal with different numbers of optical carriers and comb lines are simulated. In Section III, a proof-of-concept experiment is presented. A tunable microwave signal from 16.8 to 27 GHz is generated and its phase-noise performance is evaluated. In Section IV, a conclusion is drawn.

II. Principle

The proposed structure is shown in Fig. 1. As can be seen, multiple optical carries, spaced with an identical wavelength spacing, are sent to an optical comb generator to generate multiple optical combs. Here, an intensity modulator (IM) and a phase modulator (PM) in cascade are used to form an optical comb generator [14]. A dispersive fiber is then used to provide a wavelength-dependant time delay. Consequently, the multiple time-delayed optical combs are sent to a PD to generate a microwave signal.

Indeed, the proposed structure in Fig. 1 is similar to the structure of a photonic microwave delay-line filter [15]. It is known that a photonic microwave delay-line filter generates multiple time-delayed copies of the driving microwave signal [16], [17]. Due to constructive and destructive interferences, a periodic spectral response is generated. For the same filter structure, if the microwave signal is multiple time-delayed microwave combs, only the comb line with its frequency corresponding to the constructive interference will be obtained at the output of the system and the other comb lines will be suppressed. The key advantage of this system is that the photonic microwave delay-line filter is tunable, which enables the generation of a frequency tunable microwave or sub-terahertz wave. This is the key motivation of using a photonic microwave delay-line filter structure for frequency-tunable microwave generation.

The optical field $E_1(t)$ at the output of the optical coupler is given by

$$E_1(t) = A_1 e^{j\omega_1 t} + A_2 e^{j\omega_2 t} + \cdots + A_P e^{j\omega_p t} \tag{1}$$

where A_p and ω_p are the amplitude and frequency of the pth optical carrier, respectively, and P is the total number of optical carriers. For a flat comb with $2N+1$ optical comb lines, the optical field $E_2(t)$ at the output of the optical comb is given by

$$\begin{aligned} E_2(t) = A_1 \sum_{n=-N}^{N} e^{j(\omega_1+n\omega_m)t} + A_2 \sum_{n=-N}^{N} e^{j(\omega_2+n\omega_m)t} \\ + \cdots + A_P \sum_{n=-N}^{N} e^{j(\omega_P+n\omega_m)t}. \end{aligned} \tag{2}$$

The transfer function of the dispersive fiber is given by

$$H(j\omega) = \exp\left(j\frac{1}{2}\beta_2 L\omega^2\right)$$

where β_2 $(\mathrm{ps}^2/\mathrm{km})$ and L are the dispersion coefficient and the length of the fiber, respectively.

The optical field $E_3(t)$ at the output of the dispersive fiber is thus given by

$$\begin{aligned} E_3(t) = A_1 e^{j\omega_1 t} \sum_{n=-N}^{N} e^{jn\omega_m} \cdot e^{j\frac{1}{2}\beta_2 L(\omega_1+n\omega_m)^2} \\ + A_2 e^{j\omega_2 t} \sum_{n=-N}^{N} e^{jn\omega_m} \cdot e^{j\frac{1}{2}\beta_2 L(\omega_2+n\omega_m)^2} \\ + \cdots + A_P e^{j\omega_P t} \sum_{n=-N}^{N} e^{jn\omega_m} e^{j\frac{1}{2}\beta_2 L(\omega_P+n\omega_m)^2}. \end{aligned} \tag{3}$$

The current at the output of the PD is

$$i(t) = \Re E_3(t) E_3^*(t) \tag{4}$$

where $\Re$ is the responsivity of the PD. Here, we consider a case where the frequency spacing between any two optical carriers is larger than the PD bandwidth. Thus, the beating between any two optical carriers will not be detected by the PD. We further consider that this condition is also applied to the comb lines of the optical combs carried by different optical carriers. Mathematically, this condition is expressed as

$$(\omega_x - N\omega_m) - (\omega_y + N\omega_m) > B \tag{5}$$

where $x, y \in \{1, 2, \ldots, P\}$, P is again the number of the optical carriers, and B is the bandwidth of the PD. It then follows that the PD current is given by

$$\begin{aligned} i(t) = \Re|A_1|^2 \sum_{n=-N}^{N} e^{jn\omega_m} \cdot e^{j\frac{1}{2}\beta_2 L(\omega_1+n\omega_m)^2} \\ \cdot \sum_{m=-N}^{N} e^{-jm\omega_m} \cdot e^{-j\frac{1}{2}\beta_2 L(\omega_1+m\omega_m)^2} \\ + \Re|A_2|^2 \sum_{n=-N}^{N} e^{jn\omega_m} \cdot e^{j\frac{1}{2}\beta_2 L(\omega_2+n\omega_m)^2} \\ \cdot \sum_{m=-N}^{N} e^{-jm\omega_m} \cdot e^{-j\frac{1}{2}\beta_2 L(\omega_2+m\omega_m)^2} \\ \vdots \\ + \Re|A_P|^2 \sum_{n=-N}^{N} e^{jn\omega_m} \cdot e^{j\frac{1}{2}\beta_2 L(\omega_P+n\omega_m)^2} \\ \cdot \sum_{m=-N}^{N} e^{-jm\omega_m} \cdot e^{-j\frac{1}{2}\beta_2 L(\omega_P+m\omega_m)^2}. \end{aligned} \tag{6}$$

As can be seen from (6), each optical carrier generates precisely the same microwave components, but with different phase shifts. The microwave components at the same frequency will interfere either constructively or destructively, depending on the relative phase shifts, which can be controlled by adjusting the wavelength spacing of the optical carriers or the dispersion of the dispersive fiber. Note that the number of the detected microwave components, for a given optical comb, is limited by the PD bandwidth.

The structure shown in Fig. 1 is in fact a photonic microwave delay-line filter if the optical comb generator is replaced by an IM that is biased at the quadrature point (while holding all parameters, as in Fig. 1). The transfer function of the associated photonic microwave delay-line filter is given by

$$T(j\omega_m) = \sum_{p=1}^{P} A_p e^{j\frac{1}{2}\beta_2 L\left(2\omega_p\omega_m+\omega_m^2\right)} \tag{7}$$

where P is again the total number of the optical carriers, and ω_p and ω_m are the pth optical carrier and input microwave frequencies, respectively.

Note that the use of a multiwavelength source and a dispersive fiber to form a photonic microwave delay-line filter for the generation of an arbitrary waveform has recently been proposed [18].

A simulation of the proposed system is performed, in which the number of optical comb lines is 17 $(N = 8)$, and the number of optical carriers are one, three, and ten. In the simulation, the frequency of the input microwave drive signal is 6 GHz, the optical wavelength spacing is 0.171 nm, and the length of a dispersive fiber is 16 km and the dispersion coefficient is $\beta_2 = 20\ \mathrm{ps}^2/\mathrm{km}$. The amplitude distributions of the generated microwave harmonics are shown in Fig. 2. Assume that the microwave signal to be generated is the Jth harmonic, the electrical spurious suppression ratio (SSR), defined as the ratio between the amplitude of the Jth harmonic and the highest amplitude of the other harmonics, is the largest for the case where ten optical carriers are employed. The reason of the largest SSR is that the employment of ten optical carriers makes the photonic microwave delay-line filter have the best frequency selectivity. The frequency of the generated microwave signal can be tuned by adjusting either the modulation frequency or the carrier wavelength spacing. For example, in Fig. 2, considering the same modulation frequency of 6 GHz and ten optical carries, the multiplication factor can be tuned to be 15, 16, 14, 13, 12, and 6 by adjusting the wavelength spacing at 0.171, 0.1197, 0.1368, 0.1454, 0.1077, and 0.1112 nm, respectively.

Note that the maximum multiplication factor can be further increased by increasing the number of the optical comb lines, which is readily achievable. Thus, the multiplication factor is limited only by the bandwidth of the PD.

The frequency responses of the associated photonic microwave delay-line filter with three and ten optical carriers are shown in Fig. 3. It is clearly seen that the filter with ten optical carriers has better frequency selectivity than that with three optical carriers.

By controlling the relative time delay via adjusting the wavelength spacing of the optical carriers or the dispersion of the dispersive fiber, the peak of the spectral response of the microwave delay-line filter can be tuned to select the desired harmonic while suppressing other harmonics to ensure a largest SSR.

It is possible to tune the wavelength spacing such as the first passband of the spectral response of the associated photonic microwave delay-line filter is located at the position as the desired harmonic, while other harmonics are within the stopband. This approach, however, is convenient only for a system incorporating a large number of optical carriers. For example, for an integrated version of the proposed system, in which a large number of semiconductor laser diodes can be integrated with a PM and an IM and cascaded with a PD via a dispersive waveguide. Nonetheless, for a discrete version of the system, the number of the laser sources is limited, and thus, a wide bandwidth is expected for a large free spectral range (FSR). In this case, an alternative solution to have a good selectivity of the desired harmonic is to use less optical carriers, but smaller FSR, as shown in Fig. 3. We choose the FSR to make one passband

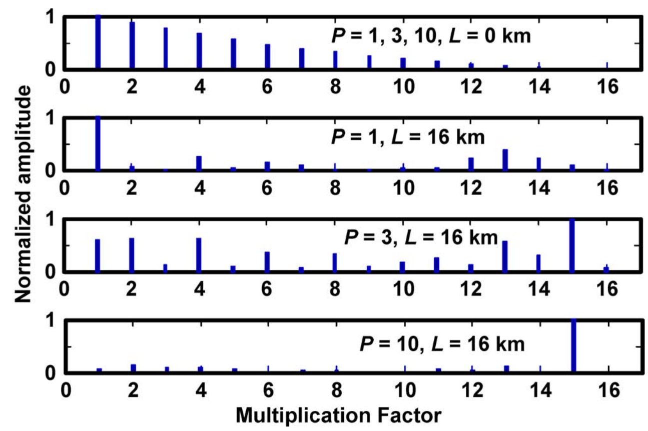

Fig. 2. Simulated amplitude distributions of the generated microwave harmonics. (*top*) Proposed system has one, three, or ten optical carriers, but with $L = 0$. (*top/middle*) Proposed system has one optical carrier with $L = 16$ km. (*bottom/middle*) Three and (*bottom*) ten optical carriers both with $L = 16$ km. Each optical carrier carries 17 optical comb lines. The wavelength spacing is 0.171 nm, the dispersion coefficient is 20 $\mathrm{ps}^2/\mathrm{km}$, and the frequency of the microwave drive signal is 6 GHz.

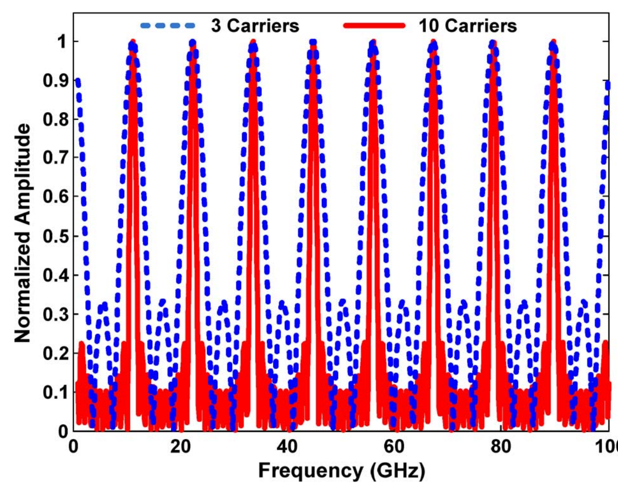

Fig. 3. Simulated frequency responses of the associated photonic microwave filter with three and ten optical carriers.

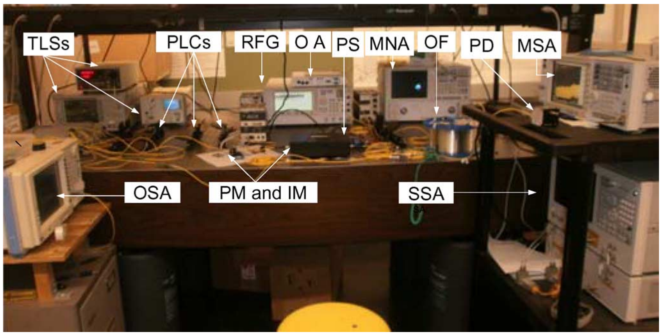

Fig. 4. Photograph of the experimental system. Optical spectrum analyzer: OSA. Tunable laser sources: TLS. Polarization controllers: PLC. Intensity modulator and phase modulator: IM and PM. RF generator: RFG. Optical amplifier: OA. RF phase shifter: PS. Microwave network analyzer: MNA. Optical fiber: OF. Photodetector: PD. Microwave spectrum analyzer: MSA. Signal source analyzer: SSA.

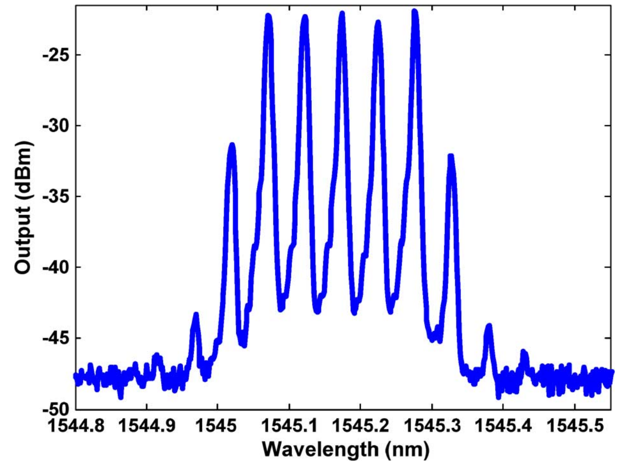

Fig. 5. Experimentally generated optical comb at λ_1.

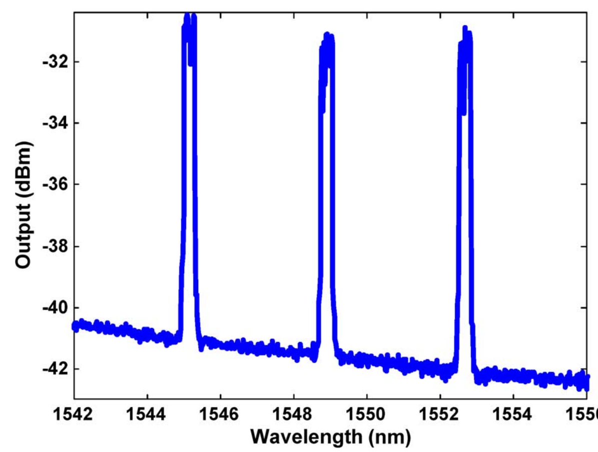

Fig. 6. Optical combs at λ_1, λ_2, and λ_3.

located at the frequency of the desired harmonic, but the nulls at the nondesired harmonics. This implies the following condition:

$$Y \cdot \mathrm{FSR} = M \cdot f_m \tag{8}$$

where Y is the number of the passband, and M is the desired multiplication factor. For example, in the simulations presented in Figs. 2 and 3, where $\mathrm{FSR} = 11.25$ GHz, it can be easily shown that the only peak number and multiplication factor that satisfy the condition given in (8) are $Y = 8$ and $M = 15$. This means that the fifteenth harmonic is selected by the eighth passband and the other harmonics do not fall in any of the passbands and will be suppressed.

III. Experiment

A proof-of-concept experiment is performed based on the setup shown in Fig. 1. A photograph of the experimental system is shown in Fig. 4.

In the experiment, the photonic microwave delay-line filter is implemented with three taps by using three optical carriers. The wavelengths of the optical carriers are $\lambda_1 = 1545.2$ nm, $\lambda_2 = 1548.9$ nm, and $\lambda_3 = 1552.6$ nm with a wavelength spacing of 3.7 nm. An IM and a PM (both with a bandwidth of 20 GHz) are cascaded to form an optical comb generator. A tunable RF phase shifter (PS) is utilized to ensure the generation of a flat optical comb. A single-mode fiber (SMF) of a length of $L = 16$ km and $\beta_2 = 20$ ps^2/km is used as a dispersive element. A PD with a bandwidth of 30 GHz is utilized to detect the microwave signal.

The generated optical comb at the optical carrier λ_1 is shown in Fig. 5.

Here, the microwave drive signal with a frequency of $f_m = 5.6$ GHz is applied to the IM and PM, as shown in Fig. 1. An RF amplifier is used to increase the power of the microwave drive signal to the IM to generate a higher number of optical comb lines.

The optical combs carried by the three optical carriers at λ_1, λ_2, and λ_3 are shown in Fig. 6. Since the wavelength spacing is 3.7 nm, which corresponds to a beat frequency of 461.6 GHz, it is too high to be detected by the PD. Therefore, the condition in (5) (i.e., the beating between any two different optical carriers or between any two optical comb lines from different optical carriers cannot be detected) is guaranteed.

We first show the operation of the system when only a single optical carrier is employed. Since only a single carrier is employed, the photonic microwave delay-line filter has a single tap; therefore, the frequency response is flat with no frequency selectivity. Fig. 7 shows the generated microwave signal when only a single optical carrier at λ_1 is on while the other two carriers are off. Here, limited by the bandwidth of the PD, up to the fifth harmonic are detected. In addition to the third-order harmonic at 16.8 GHz generated, other harmonics are also generated. As can be seen, despite the flat optical comb, the microwave harmonics do have a shape. This is because of the interference of the comb lines within an optical comb due to fiber dispersion.

We then switch on all the three optical carriers. The photonic microwave delay-line filter has three taps. Fig. 8 shows the detected microwave signal when all the three optical carriers are on. As can be seen, only the third harmonic at 16.8 GHz is detected. This is because the frequency response of the filter is designed such that the frequency corresponding to the third-order

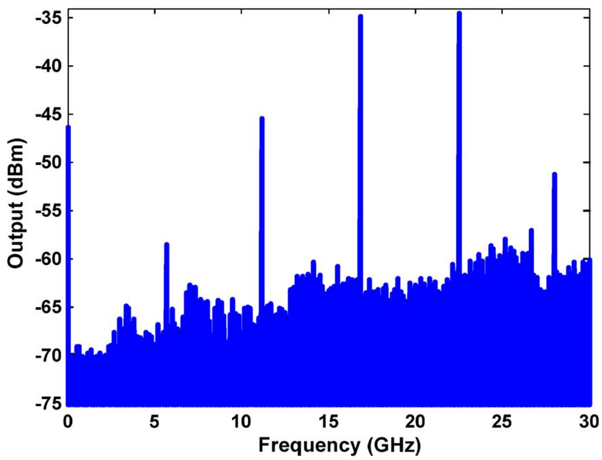

Fig. 7. Detected microwave signal when only one optical carrier is on.

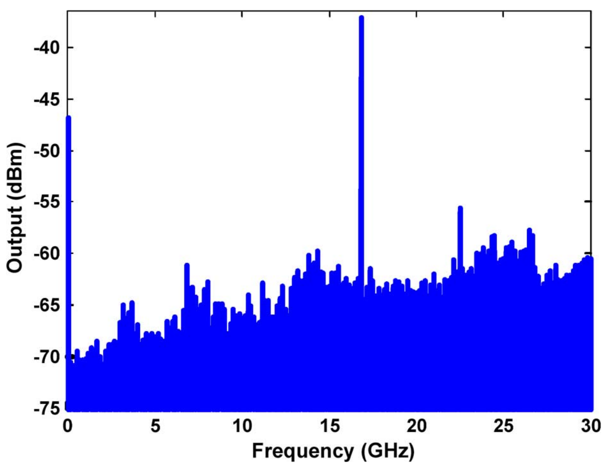

Fig. 8. Detected microwave signal when the three optical carriers are on.

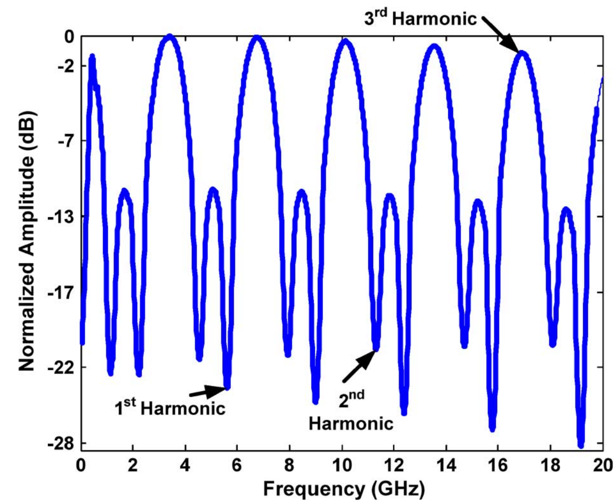

Fig. 9. Frequency response of the associated photonic microwave delay-line filter. The frequency response is designed such that the third-order harmonic is selected while the first- and the second-order harmonics are suppressed.

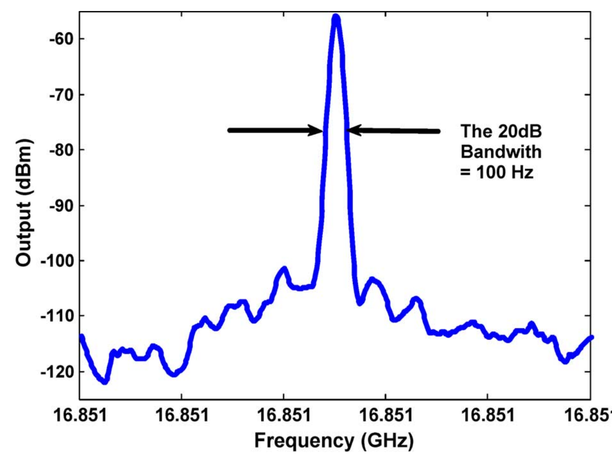

Fig. 10. Zoom-in view of the generated microwave when three optical carriers are employed. Here the frequency of the microwave drive signal is 5.6 GHz.

harmonic has a resonance peak and the other harmonics are suppressed.

To better explain the result shown in Fig. 8, we perform a measurement of the frequency response of the associated photonic microwave delay-line filter. To do the measurement, all parameters of the system are kept the same, except that the PM is removed, and the spectral response is measured by a vector network analyzer.

As can be seen in Fig. 9, the frequency of the third-order harmonic is located at the peak of the frequency response of the associated photonic microwave delay-line filter, while the frequencies of the first- and the second-order harmonics are located at the nulls of the frequency response of the associated photonic microwave delay-line filter. This explains the suppression of the first- and the second-order harmonics, which is confirmed by the experimental result in Fig. 8. The measurement in Fig. 9 is limited to 20 GHz because of the limited bandwidth of the used IM. We note also that the used vector network analyzer has a dc block, which explains the drop in the frequency response at dc, and that the connecting wires have a large attenuation at high frequencies, which explains the attenuation at high frequencies.

We note that the power of the generated microwave signal in Fig. 8 is a little lower than that of the same microwave signal in Fig. 7 where only one carrier is used. This lower power is due to the frequency of the generated microwave signal is not precisely located at the peak of the frequency response of the associated photonic microwave delay-line filter.

The quality of the generated microwave signal is evaluated. Since the generated microwave signal is generated by the beating of the optical comb lines within the same optical comb, the quality of the generated signal is determined by the quality of the microwave drive signal [19]. Fig. 10 shows a zoom-in view of the generated microwave signal. It can be seen that the 20-dB bandwidth is as small as 100 Hz, confirming the high quality of the generated microwave signal.

To further evaluate the quality of the generated microwave signal, the phase noise is measured, as shown in Fig. 11. Here, the phase noise of the microwave drive signal is also shown as a comparison. It is known that the phase-noise degradation for a multiplication factor of M is given by $20\log_{10} M$. Since the multiplication factor is 3, the degradation is 9.5 dB, which is confirmed by the phase-noise measurement in Fig. 11 [19]. Note that the phase-noise degradation of the generated microwave signal at higher offset frequencies ($> 10^3$ Hz) is more than

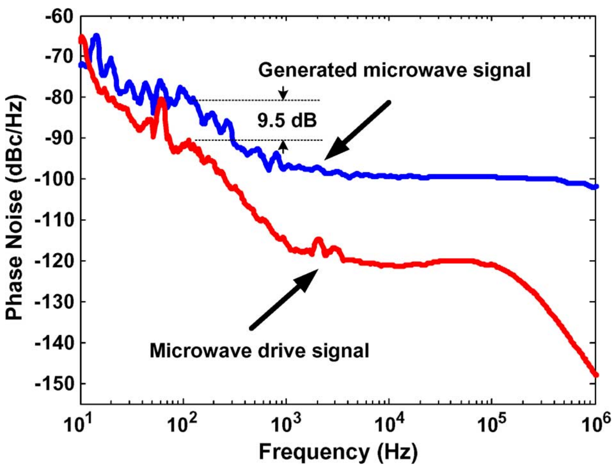

Fig. 11. Phase noise of the generated signal (shown in Fig. 7) and the derive signals.

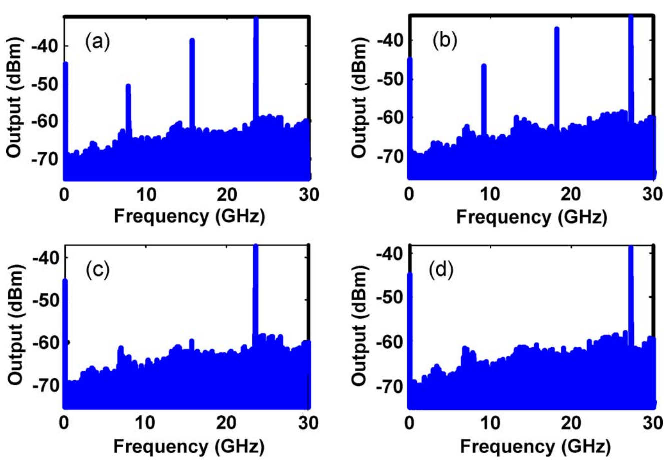

Fig. 12. Generated microwave signals. (a) One optical carrier and the frequency of the microwave drive signal is 7.8 GHz. (b) One optical carrier and the frequency of the microwave drive signal is 9 GHz. (c). Three optical carriers and the frequency of the microwave drive signal is 7.8 GHz. (d) Three optical carriers and the frequency of the microwave drive signal is 9 GHz.

9.5 dB, which has resulted due to the additional phase noise from the generation system.

The tunability of the system is also investigated. The tunability can be realized by either adjusting the modulation frequency or the wavelength spacing. For fine tuning, both the modulation frequency and the wavelength spacing should be adjusted. Fig. 12 shows the generated microwave signals when the frequency of the microwave drive signal is tuned at 7.8 and 9 GHz, while all other parameters are kept unchanged. For the two cases, one optical carrier and three optical carriers are employed. As can be seen, when one optical carrier is employed, although a microwave signal at the third-order harmonic, 23.4 and 27 GHz, is generated, the SSR is small since other harmonics are not sufficiently suppressed, as shown in Fig. 12(a) and (b). When the three optical carriers are all on, due to the selectivity provided by the photonic microwave delay-line filter, a microwave signal at the third-order harmonic is generated and other harmonics are suppressed, as shown in Fig. 12(c) and (d). A high SSR is maintained.

The stability of the operation is also studied. To do so, we allow the system to operate in a room environment for 3 h. No visible changes in the microwave power are observed. The excellent stability is mainly due to the fact that the system has a structure with a finite impulse response (FIR), which enables a stable operation. In addition, the IM is biased at the quadrature point, which makes the system less sensitive to bias drift.

IV. Conclusion

We have proposed and experimentally demonstrated a novel method to generate a frequency-tunable microwave signal based on time-delayed optical combs. The fundamental operation of the system is to employ an optical delay-line structure to form a photonic microwave delay-line filter to select one of the beat frequencies without the need of optical or microwave filters. The key contribution of the work is that a tunable microwave signal with a large multiplication factor and high SSR can be generated with a greatly simplified structure. The frequency tunability was achieved by simply tuning the frequency of the microwave drive signal. The generation of a microwave signal at 24.3 and 27 GHz by applying a microwave drive signal at 7.8 and 9 GHz was demonstrated. The generated signal frequency can be extended to the sub-terahertz range by utilizing a fast PD. The quality of the generated microwave signal was also evaluated. It was shown that the phase noise of the generated microwave signal was determined by the phase noise of the microwave drive signal for an offset frequency smaller than 10^3 Hz. When the offset frequency is greater than 10^3 Hz, the phase noise introduced by the generation system will play a more important role. The use of a high-quality laser array and low-noise optical and electronic amplifiers will reduce the phase noise at higher frequency offset.

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