Synthesis of Millimeter-Wave Power Spectra Using Time-Multiplexed Optical Pulse Shaping

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***Abstract*—Millimeter-wave (MMW) electrical power spectra are flexibly synthesized by integrating fast wavelength switching, optical frequency comb generation, spectral line-by-line pulse shaping, and optical-to-electrical conversion. Control over generated RF power spectra is exercised through the choice both of the optical parent waveforms and of the wavelength switching patterns. Discrete or comb-like MMW power spectra are generated using periodic wavelength switching, while nearly continuous MMW spectra can be obtained when wavelengths are switched according to a pseudorandom bit stream.**

***Index Terms*—Microwave photonics, optical signal processing, pulse shaping.**

I. Introduction

PHOTONICALLY assisted microwave and millimeter-wave (MMW) generation has attracted strong research interest [1]–[4]. In addition to generation of simple MMW tones, arbitrary MMW signal generation methods making use of optical pulse shapers are of particular interest [5]–[8]. Generation of arbitrary ultrawideband (UWB) MMW signals as well as shaping of the UWB power spectra have been reported [7]–[9]. However, these photonic methods are usually only slowly reprogrammable. We have recently demonstrated a versatile new time-multiplexing scheme [10] that integrates high-speed wavelength switching, optical frequency comb generation, and optical line-by-line pulse shaping [11], which allows rapid (~100 ps) switching between different RF signals. In the previous work, generated RF waveforms were characterized only in the time domain. In this letter, we describe new experiments in which our time-multiplexed pulse shaping scheme is applied to achieve flexible photonic-assisted tailoring of MMW power spectra. We demonstrate the ability to manipulate both the envelope of the generated power spectrum and the frequency spacing of discrete MMW frequency components within this envelope.

II. Experiments and Results

Our flexible MMW power spectral synthesis setup is composed of three key parts, schematically shown in Fig. 1(a): a rapid wavelength switcher, an optical frequency comb generator followed by a line-by-line pulse shaper, and a photodetector for optical-to-electrical domain conversion. Here, two continuous-wave (CW) lasers (with center wavelengths of $\lambda_a = 1541.12$ and $\lambda_b = 1541.99$ nm) each followed by a $LiNbO_3$ intensity modulator (IM) are used to provide rapid wavelength switching. IM1 (for λ_a) and IM2 (for λ_b) are driven by a programmable data port (Q) and inverted data port $(\overline{Q})$ of a bit-error-ratio test set [(BERT) Agilent N4906B with 13.5 GHz bandwidth], respectively. The time-multiplexed CW outputs are combined via an optical coupler and directed to an optical frequency comb generator [12], which is a $LiNbO_3$ phase modulator (PM) driven at a frequency of $f_{\rm rep} = 10$ GHz, using the same clock as the BERT. The optical phase modulation frequency determines the optical comb line spacing. These phase-modulated CW (PMCW) combs are then manipulated by a spectral line-by-line shaper, using a liquid crystal modulator (LCM) to generate user-specified optical waveforms. Detailed descriptions of our reflective line-by-line shaper can be found within [11].

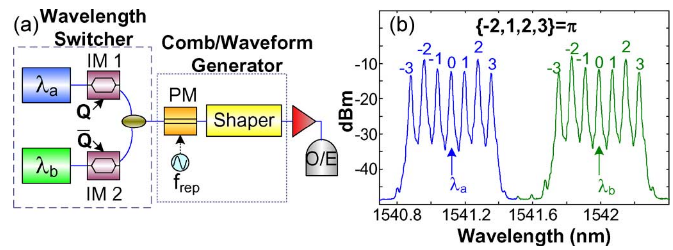

Fig. 1. (a) Schematic of the experimental setup. (λ_a, λ_b): two CW lasers; $f_{\rm rep}$: comb frequency spacing; O–E: optical-to-electrical conversion via a photodetector. (b) Optical spectrum of the seven-line selected phase-modulated CW combs when both CW lasers are on.

In order to enable flexible MMW power spectral synthesis, different LCM regions may be programmed to generate different waveforms; essentially different regions of the LCM act as a waveform bank. Different regions of the LCM (hence different waveforms) are selected by rapidly changing the corresponding input wavelength (within 100 ps in our demonstrations). An optical amplifier is used after the shaper, and the waveform intensities and electrical spectra are detected via a 60-GHz bandwidth photodiode followed by 50-GHz sampling scope or electrical spectrum analyzer (ESA). An optical spectrum analyzer with 0.01 nm resolution is used to measure the optical comb spectra. Fig. 1(b) shows the PMCW combs when both CW lasers are turned on. Here, seven lines are selected by the shaper from each comb. In our PMCW comb generation process, comb lines labeled (−2, 1, 2, and 3) are generated π out of phase with the rest of the lines.

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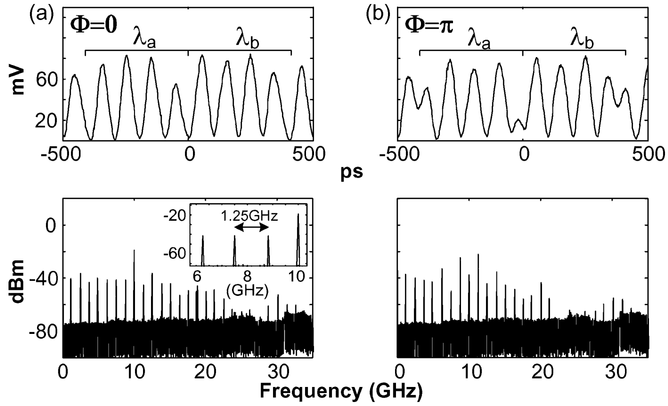

Fig. 2. Sampling scope and ESA traces of rapid MMW waveform phase switching using two spectral lines from each comb. Each waveform occupies 400 ps. (a) Two waveforms in phase. (b) Phase modulation is π.

Using our approach, a comb of discrete MMW frequencies can be flexibly synthesized. The MMW frequency spacing is determined by the length of the waveform switching pattern Q, while the envelope of the MMW power spectrum can be tailored by choice of optical parent waveforms and the switching pattern between them. In Fig. 2, we begin with simple cases where only lines $\{-1, 0\}$ from each optical comb are allowed to pass the shaper. Here, a repetitive data pattern $Q = [1111\ 0000]$ is fed to IM1 where each bit occupies 100 ps; accordingly we switch between parent waveforms every 400 ps. Two 10-GHz cosine intensity waveforms are observed on the sampling scope. The corresponding intensity waveforms from the λ_a and λ_b combs are labeled within the figures. The sampling scope trace in Fig. 2(a) shows the measured waveform when no optical phase control is applied, giving identical cosine waveforms in each 400-ps waveform frame. The sampling scope trace in Fig. 2(b) shows the measured waveform when a π phase is applied to λ_a comb line $\{-1\}$, so that an MMW waveform with abrupt π phase shifts (delay of 50 ps) occurs every other 4 bits. The MMW power spectra measured by the ESA are also shown in Figs. 2(a), (b) for phase controls of (0, π), respectively. The 800-ps period of Q determines the discrete MMW signal spacing of 1.25 GHz [inset, Fig. 2(a)]. Ideally, the zero optical phase control case would generate a pure 10-GHz MMW tone. The experimental RF power spectrum shows a dominant 10 GHz peak as expected; the finite (>17.7 dB) suppression of the remaining comb lines provides a measure of the spectral impurity, which arises in part due to finite rise and fall time of the switching pattern. In the abrupt π phase shift case, the 10 GHz line in the MMW spectrum is suppressed by 18.5 dB, with energy redistributed to nearby (mainly $\pm$1.25 GHz) lines. The suppression demonstrated in the phase shift case, which is expected for any waveform with a 50% duty cycle π phase shift, confirms the fidelity of our waveform generation system.

Fig. 3 demonstrates synthesis of different MMW spectral content over a very broadband, in which wavelength switching is controlled using a 16-bit data pattern of $Q = [1111\ 0000\ 0000\ 0000]$, corresponding to 625-MHz MMW frequency spacing. In Figs. 3(a) and (c), MMW lines centered at 10 and 30 GHz are generated by switching between cosines of 10 and 30 GHz repetition rate (by selecting λ_b optical comb lines $\{-1, 0\}$ and λ_a optical comb lines $\{-2, 1\}$ with π phase applied to line $\{-2\}$, respectively). Figs. 3(b) and (d) show the synthesized MMW power spectra with switching between 40 GHz (by selecting λ_a optical comb lines $\{-2, 2\}$) and the 10-GHz λ_b comb waveform. As expected, the spectra show dominant peaks at 10 and 30 GHz in Figs. 3(a) and (c) and 10 and 40 GHz in Figs. 3(b) and (d). We attribute the observed weak extra MMW peaks (e.g., in Fig. 3(a), the 20 and 40 GHz peaks) to finite power extinction of the pulse shaper ($\sim$20 dB) implemented in our experiments.

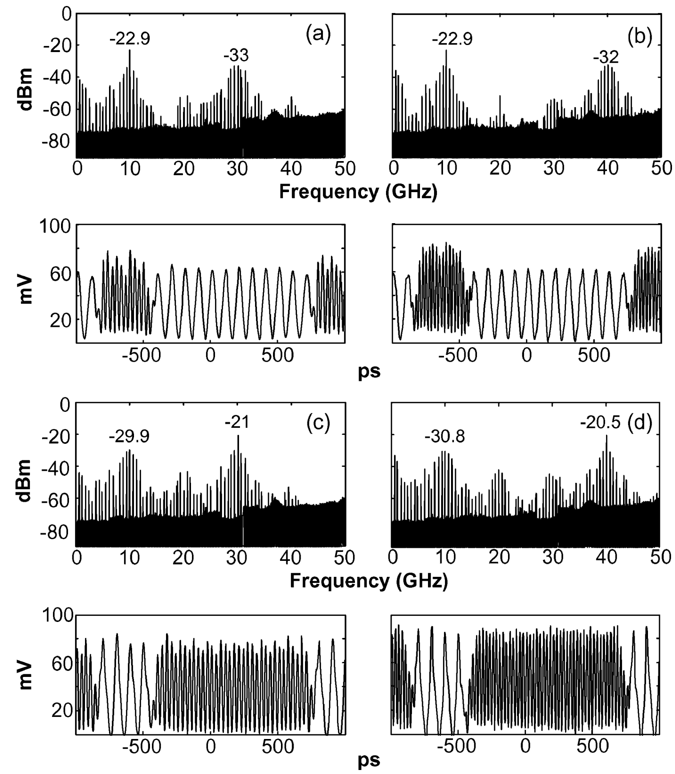

Fig. 3. The 625-MHz spacing MMW comb generations and the corresponding sampling scope traces. (a), (c) Fast switching between (10, 30) GHz sinusoids; (b), (d) Fast switching between (10, 40) GHz sinusoids. The peak power values are denoted in dBm. ESA resolution bandwidth is 100 kHz.

In these examples, we are able to control the relative amplitudes of the main MMW spectral peaks by choosing the duty cycle of the data pattern. The idea is that the durations of the parent waveforms (each of which corresponds to a different RF frequency) determine the total power received by the photodetector and thus affect the amplitude of the corresponding RF peak. In contrast to Fig. 2, where the two parent waveforms have equal temporal durations, here the λ_a and λ_b waveforms are turned on 25% and 75% of the time, respectively. This places more energy into the λ_b waveform. Furthermore, the longer duration of the λ_b (10 GHz) waveform gives the sharper spectral peaking. Together these effects enhance the 10 GHz line by $\sim$10 dB compared to the 30 and 40 GHz peaks in Figs. 3(a) and (b), respectively. Figs. 3(c) and (d) show the converse case, in which a complementary waveform switching pattern with the higher frequency waveforms now turned on 75% of the time enhances the 30 and 40 GHz peaks, respectively. Note that manipulation of relative RF spectral amplitudes, as shown

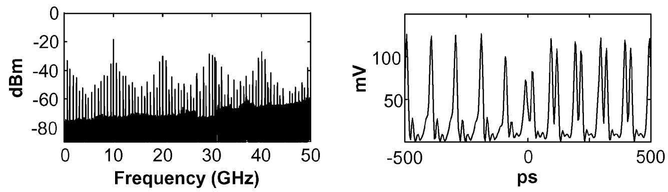

Fig. 4. ESA and zoomed sampling scope trace of fast switching between (transform-limited, doublet) pulses.

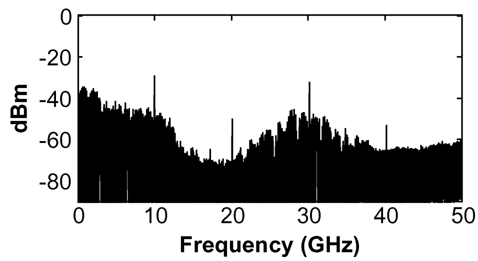

Fig. 5. Continuous MMW spectrum generation when a pseudorandom bit sequence is used as the optical waveform switching pattern.

here, could also be accomplished by controlling optical amplitudes in the pulse shaper, but without the possibility of rapid modulation under electronic data control.

Fig. 4 shows MMW signal synthesis with $Q = [1111\ 1111\ 0000\ 0000]$ and switching between transform limited pulses (λ_a comb) and doublet pulses (λ_b comb). The MMW spectrum spans the entire 0- to 50-GHz ESA bandwidth, with a modulated envelope peaking at 10 GHz and its harmonics.

Fig. 5 shows the MMW power spectrum when a pseudorandom bit stream of length $2^7 - 1$ is applied as the switching pattern between the 30-GHz (λ_a comb) and 10-GHz (λ_b comb) cosine waveforms. A nearly continuous MMW spectrum can be obtained using this approach. One may implement the phase shift approach demonstrated in Fig. 2 to suppress the strong carrier of the optical waveform (the 10- and 30-GHz peaks in the current case) if needed. This can be accomplished, e.g., in the current case, by adding π-shifted cosines of 10 and 30 GHz into the waveform sequence.

III. Discussion and Summary

From the above examples, we need to emphasize here that the current spectral limitation is set by the available bandwidth of the photodetector and the ESA. Under proper driving condition, the initial PMCW comb optical bandwidth may exceed 400 GHz, and further nonlinear spectral broadening is possible [11]. One may envision flexible MMW spectral synthesis with substantially higher complexity and covering from the RF range all the way into the terahertz regime. We also note that although in our current demonstration, the switching pattern frequency is identical to the comb repetition frequency at 10 GHz; however, one should gain more freedom in synthesizing MMW power spectra when the two frequencies are not identical. If the frequency spacing of the optical comb is made much smaller than the current 10 GHz, our scheme could find application in the control of RF power spectra in the UWB range defined by the FCC as 3.1–10.6 GHz.

In summary, a novel time-multiplexed optical pulse shaping scheme for flexible MMW power spectra synthesis has been demonstrated. By adjusting the switching pattern between different "parent" RF waveforms, the line spacing and spectral amplitude profile of generated MMW frequency combs can be tailored. Nearly continuous MMW spectra are generated by using long pseudorandom bit streams as the switching pattern between waveforms and may find great potential for the shaping of UWB power spectra.

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