Picosecond flat-top pulse generation by low-bandwidth electro-optic sinusoidal phase modulation

Naum K. Berger,[1,3] Boris Levit,[1] Baruch Fischer,[1] and José Azaña[2,4]

[1]*Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa, 32000, Israel*
[2]*Institut National de la Recherche Scientifique—Énergie, Matériaux et Télécommunications, 800 de la Gauchetière Ouest, Suite 6900, Montreal, Quebec H5A 1K6, Canada*
[3]*chrberg@techunix.technion.ac.il*
[4]*azana@emt.inrs.ca*

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We report the first experimental demonstration to our knowledge of a microwave frequency upshifting system based on phase modulation. A sequence of flat-top optical and RF pulses at a repetition rate of 18.22 GHz, each with a FWHM time width of ≈25 ps, is generated from a sinusoidal RF tone of only 3.680 GHz, in good agreement with our analytical and numerical calculations. A simple explanation of this technique based on Talbot effect theory is provided. The practical limitations and capabilities of the phase-modulation-based frequency upshifting approach for ultrabroadband RF waveform generation are also discussed. © 2008 Optical Society of America

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Novel techniques for the generation of high-frequency microwave signals are required for various applications, including ultrawideband radio-frequency (RF) communication systems, pulsed radar, and fiber-wireless communications. Current electromagnetic arbitrary waveform generation is limited to the range below ≈5 GHz. Several photonics-based techniques have been demonstrated for generation of microwave waveforms in the gigahertz and multiple-tens-of-gigahertz ranges [1–4]. An interesting method is based on frequency upshifting of a narrowband microwave signal [1–3]. In this technique the original microwave signal is imaged into a temporally compressed replica by means of a simple and practical fiber-based system, consisting of an intensity electro-optic (EO) modulator (to transfer the microwave signal into the optical domain) surrounded by two dispersive fibers, in which an ultrashort pulse is used as the optical input [1]. We have demonstrated that the operational bandwidth of a frequency upshifting system can be enhanced by exploiting a temporal self-imaging (Talbot) effect in optical fiber [2,3], which can be applied whenever the microwave signal to be temporally compressed is an arbitrary periodic RF signal. However, in a frequency upshifting scheme based on intensity modulation, the output pulse shapes are just temporally compressed replicas of the input microwave waveforms (e.g., only sinusoidal waveforms could be obtained from input RF tones [1–3]). To overcome this limitation, the use of phase EO modulation has been suggested instead: Torres-Company *et al.* [4] have numerically shown that a wide variety of user-defined high-frequency periodic microwave waveforms could be achieved at the system output by appropriately setting the different system parameters (dispersions and input microwave modulating signal). Like frequency upshifting based on intensity modulation, the output microwave bandwidth can be higher than the input modulation bandwidth. The distinctive feature of the frequency upshifting approach based on phase modulation is that interesting waveforms different from that driving the EO modulator can be directly generated at the system output. In this Letter, we provide for the first time to our knowledge an experimental demonstration of the microwave frequency upshifting technique based on phase modulation. Specifically, we experimentally generate a flat-top pulse train (50% duty cycle) at a repetition rate of ≈18 GHz from an ≈3.68 GHz RF tone. This specific demonstration is intrinsically relevant, as flat-top pulse generation is of interest in both the microwave and the optical domains for applications requiring the use of a well-defined square-like time window.

It has been previously demonstrated that flat-top optical pulses can be synthesized by propagation of sinusoidally phase-modulated CW light through a suitable dispersive fiber [5]. The scheme proposed here for flat-top pulse generation can be easily explained as an upgrading of this previous method. Thus, we consider first the problem of sinusoidal phase modulation of CW light followed by linear dispersion [5]. The complex amplitude of the optical signal at the phase modulator output is $\exp[iA\sin(\omega_m t)] \equiv \Sigma_{n=-N}^{N} J_n(A)\exp(in\omega_m t)$, where $J_n(A)$ is the Bessel function of the first kind and order n, A is the modulation index, ω_m is the angular modulation frequency, and $2N+1$ is the number of nonzero harmonics of the modulation. After propagation through a section of dispersive fiber with first-order group-velocity dispersion β_2 and length L, the output optical pulse can be written as

$$E_{\text{out}}(t) = \sum_{n=-N}^{N} J_n(A)\exp(-i\beta_2 L n^2 \omega_m^2/2)\exp(in\omega_m t). \quad (1)$$

For fiber lengths that are integer multiples of the Talbot distance $L_T = 4\pi/(\beta_2\omega_m^2)$ (so-called integer

Talbot distances) the first exponent in Eq. (1) is equal to unity, and the output waveform is a replica of that at the fiber input (phase-modulated CW light) [5]. Our interest here is focused on a particular case of the so-called fractional temporal Talbot phenomenon, i.e., when the dispersive fiber length is fixed to $L = mL_T/4$, m being an arbitrary odd integer. From the equations governing the temporal Talbot effect [5], it can be demonstrated that in this case the output signal is a periodic train of nearly flat-top pulses (50% duty cycle) when the modulation index is set to $A = \pi/4$. In this basic approach, the repetition frequency (and associated bandwidth) of the output flat-top pulses is fixed by the input modulation frequency (ω_m). Frequency upshifting could be used to overcome this limitation [1–4]. This can be implemented by adding a dispersive delay line before the phase EO modulator and using an input ultrashort pulse source instead of CW light; see the diagram in Fig. 1. An ultrashort optical pulse, e.g., from a mode-locked fiber laser, is first stretched by the input dispersion, then sinusoidally phase modulated, and finally compressed by the output dispersion. The spectrum of the compressed optical waveform at the system output can be expressed as follows:

$$F_{\text{com}}(\omega) = \sum_{n=-N}^{N} J_n(A) F_{\text{las}}(\omega - n\omega_m) \times \exp[-iM_t\beta_2^{(1)}L_1(\omega - n\omega_m/M_t)^2/2] \times \exp[-i\beta_2^{(2)}L_2 n^2 \omega_m^2/(2M_t)], \quad (2)$$

where $F_{\text{las}}(\omega)$ is the spectrum of the ultrashort laser pulse, $\beta_2^{(1)}L_1$ and $\beta_2^{(2)}L_2$ are the first-order dispersions of the input and output dispersive fibers, respectively, and $M_t = (\beta_2^{(1)}L_1 + \beta_2^{(2)}L_2)/\beta_2^{(1)}L_1$ will be referred to as the temporal magnification factor. To achieve temporal compression (i.e., frequency upshifting), the system must be configured so that $|M_t| < 1$: The input and output dispersions must be of opposite signs. We assume now that the spectrum of the input laser pulse is sufficiently broad such that we can neglect the harmonic shifts in $F_{\text{las}}(\omega - n\omega_m)$ and $F_{\text{las}}(\omega - n\omega_m/M_t)$. Mathematically, the following condition needs to be satisfied over the full bandwidth of the input pulse: $|F_{\text{las}}(\omega) - F_{\text{las}}(\omega - N\omega_m/M_t)|/|F_{\text{las}}(\omega)| \ll 1$. For a Gaussian laser pulse with duration (FWHM) τ, this condition is strictly met when $\omega_m \ll 0.7M_t/(N\tau)$. Under this assumption, we can replace $F_{\text{las}}(\omega - n\omega_m)$ in Eq. (2) with $F_{\text{las}}(\omega - n\omega_m/M_t)$. Taking the Fourier transform of Eq. (2), we obtain for the output time waveform

$$E_{\text{com}}(t) = E_{\text{str}}(t) \sum_{n=-N}^{N} J_n(A) \times \exp[-iM_t\beta_2^{(2)}L_2 n^2(\omega_m/M_t)^2/2] \times \exp[in(\omega_m/M_t)t], \quad (3)$$

where $E_{\text{str}}(t)$ is the laser pulse temporally stretched by a dispersive line with effective dispersion $M_t\beta_2^{(1)}L_1$. The compressed optical waveform given by Eq. (3) has a form similar to Eq. (1) with the following key differences: (i) the repetition rate (and associated bandwidth) of the output pulses is increased by $1/M_t(|M_t| < 1)$, i.e., output repetition rate $= \omega_m/M_t$; (ii) the effective dispersion is $M_t\beta_2^{(2)}L_2$ and (iii) the pulse train at the system output is modulated by $E_{\text{str}}(t)$ (slow-varying envelope). Based on the analogy between Eq. (3) and Eq. (1), frequency-upshifted flat-top pulses can be obtained at the system output if the following condition is satisfied: $M_tL_2 = mL_T/4$, where the Talbot distance L_T is now calculated for the increased frequency ω_m/M_t, i.e., $L_T = 4\pi M_t/(\beta_2^{(2)}\omega_m^2)$. As for a frequency upshifting system using intensity modulation [3], the maximum output electrical bandwidth is fundamentally limited by the input optical bandwidth. The condition imposed above on ω_m is actually a condition for the maximum achievable output electrical bandwidth depending on the input pulse width, i.e. $\Delta\omega_{\text{com}} \approx (N\omega_m)/M_t \ll 0.7/\tau$. However, in practice, the maximum achievable bandwidth may be limited by the presence of high-order dispersion terms in the dispersive lines [3].

The experimental system demonstrated here (schematic shown in Fig. 1) was designed to achieve frequency upshifting by a factor of ≈ 5 ($M_t = 0.206$). As for the input dispersion, we used a dispersion compensating fiber (DCF) providing a total first-order dispersion $\beta_2^{(1)}L_1 = 1515.2\ \text{ps}^2$. Its second-order dispersion was compensated by dispersion shifted fiber (True Wave). As for the output dispersion, 56.695 km of standard SMF-28 was employed ($\beta_2^{(2)}L_2 = -1203.8\ \text{ps}^2$). According to the theory introduced above, this system could be reconfigured to synthesize flat-top pulses with different repetition rates (and associated pulse durations and bandwidths) by simply tuning the input modulation frequency ω_m to satisfy the corresponding fractional Talbot condition (free parameter m). Assuming an input Gaussian laser pulse with a width $\tau = 1$ ps, we observed by numerical simulations that for purely linear dispersions, the output flat-top pulses start becoming

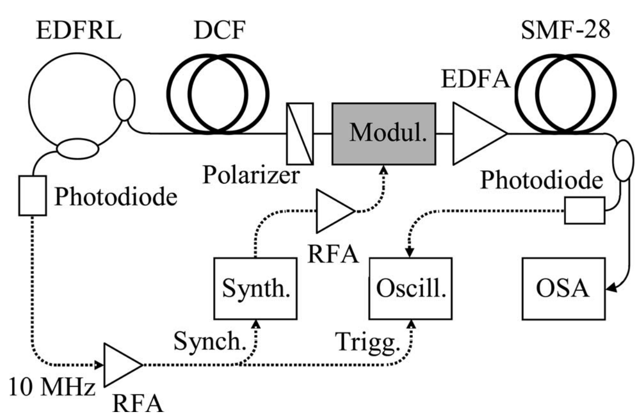

Fig. 1. Schematic of the experimental setup. EDFRL, erbium-doped fiber ring laser; Modul., EO phase modulator; EDFA, erbium-doped fiber amplifier; RFA, RF amplifier; Synch., synchronization; Trigg., triggering; Synth., RF synthesizer; OSA, optical spectrum analyzer; Oscill., sampling oscilloscope.

visibly distorted for frequencies higher than $\omega_m/(2\pi)=11.057$ GHz (from the fractional Talbot condition, with $m=9$), which would translate into a multiplied output frequency (repetition rate) $\omega_m/(2\pi M_t)$ ≈ 59.3 GHz. However, when considering the measured values of the high-order dispersion terms in the dispersive fibers used, our simulations show that slight distortions in the synthesized flat-top waveforms can be already observed for an input modulation frequency $\omega_m/(2\pi)=6.384$ GHz ($m=3$), corresponding to a multiplied output frequency of 31.065 GHz.

In our experiments, a passively mode-locked erbium-doped fiber ring laser was used as the optical pulse source. It was operated at a wavelength of $\approx$1550 nm and generated $\approx$1 ps optical pulses at a 10 MHz repetition rate. The measured input laser spectrum is shown in the inset of Fig. 2(a). The laser pulse was first stretched by the input dispersion (DCF) and then sinusoidally phase modulated by an EO modulator. The detected RF signal of 10 MHz from the laser was used for synchronization of an RF synthesizer supplying the voltage (sinusoid) to the modulator. The input modulation frequency was fixed to $\omega_m/(2\pi)=3.680$ GHz ($m=1$). The modulated optical pulses were finally compressed by the second dispersion (SMF-28). Figure 2(a) shows the optical pulse train generated at the system output as measured with a photodiode attached to a sampling oscilloscope (both with a 50 GHz bandwidth). The multiplied output repetition rate, obtained from the Fourier transform of this oscillogram, is 18.22 GHz, which is in good agreement with the theoretically expected multiplied frequency of 17.86 GHz ($M_t=0.206$). The output pulse train is modulated by a temporal envelope given by the dispersed input laser pulse $E_{\mathrm{str}}(t)$; notice that this envelope closely resembles the input pulse spectrum, as the dispersion was sufficiently high to induce frequency-to-time conversion. Figure 2(b) shows the detail of two of the synthesized pulses, clearly evidencing flat-top reshaping with an estimated FWHM time width for each pulse of $\approx$25 ps. The numerically calculated RF spectrum of one of these pulses, shown in the inset of Fig. 2(b), exhibits the expected sinc-like shape with a full bandwidth larger than 50 GHz, which explains in part the slight distortions observed in the measured flat-top waveforms.

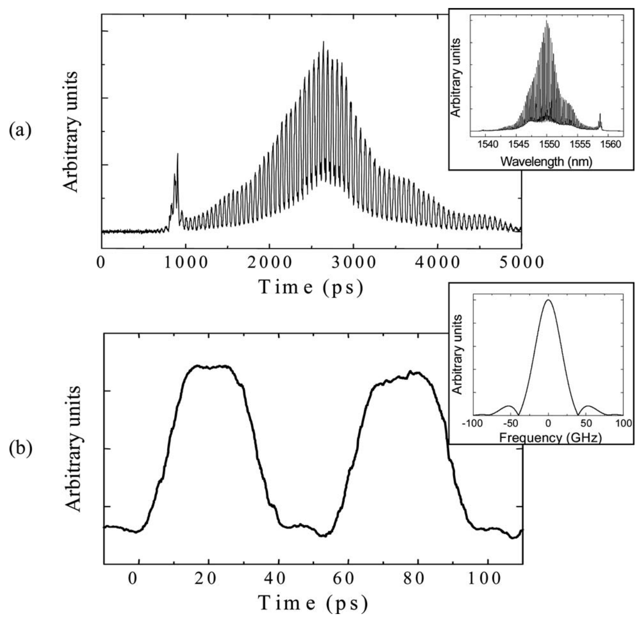

Fig. 2. (a) Modulated pulse train experimentally measured at the system output (inset, measured input laser pulse spectrum). (b) Detail of the measured individual pulses with a nearly flat-top shape (inset, calculated RF spectrum of one of these pulses). The input modulation frequency is 3.680 GHz, and the multiplied output frequency (repetition rate) is 18.22 GHz.

In conclusion, we have provided the first experimental demonstration to our knowledge of a microwave frequency upshifting system based on phase modulation. A sequence of nearly flat-top pulses at a repetition rate of 18.22 GHz has been generated from a sinusoidal RF tone of only 3.680 GHz, in good agreement with our analytical and numerical calculations.

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