Frequency shifting of microwave signals by use of a general temporal self-imaging (Talbot) effect in optical fibers

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A simple and practical microwave frequency-shifting technique based on a general temporal self-imaging (GTSI) effect in optical fiber is proposed, formulated, and experimentally demonstrated. The proposed technique can be applied to an arbitrary periodic microwave signal (e.g., a microwave tone) and provides unparalleled design flexibility to increase the frequency of the input microwave signal up to the desired value (limited only by the photodetector's bandwidth). For instance, we demonstrate frequency upshifting of microwave tones from ≈10 to ≈50 GHz and from ≈40 to ≈354 GHz. These results also represent what is to the authors' knowledge the first experimental observation of GTSI phenomena. © 2004 Optical Society of America

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The development of novel techniques for the generation, control, and manipulation of high-frequency microwave signals is becoming increasingly important for a multitude of scientific and industrial applications, including radio-frequency (RF) communications, pulsed radar, and fiber-wireless communication systems.[1] The generation of RF radiation (tones) above 40 GHz by conventional methods (electronics) is extremely complex and costly. Moreover, current electromagnetic arbitrary waveform generation is limited to a range below ≈2 GHz. Photonically assisted techniques can drastically enhance the performance of current electronic systems for the generation and manipulation of microwave signals.[1,2] One interesting method for generating high-frequency microwave signals is based on frequency upshifting of a low-frequency microwave signal.[2] In this method the original microwave signal is imaged into a temporally compressed replica by a simplified temporal imaging (TI) system (time lens + dispersion).[3] Although it is simple and practical, this conventional approach is limited with respect to the maximum RF that can be generated in practice. This bandwidth limitation is in fact typical of this class of simplified TI system.[3] Compared with an ideal TI system (dispersion + time lens + dispersion),[4] a simplified TI system leads to a nonfocused image in time. A nonfocused image manifests itself as classic dispersion in which slow phenomena appear clearly but fast phenomena (high frequencies) are filtered out. This nonfocused imaging process limits drastically the maximum microwave frequency that can be handled (e.g., generated) by the TI system. For example, the maximum RF that could be generated with the system demonstrated in Ref. 2 was 25 GHz (from a 10-GHz tone).

Here we propose and experimentally demonstrate an alternative approach to frequency shifting of microwave signals. Our approach is applicable whenever the original microwave signal to be temporally imaged (compressed) is a periodic signal (e.g., a microwave tone or any arbitrary periodic RF signal) and is based on the so-called general temporal self-imaging (GTSI) effect.[5] By exploiting this effect, one can use a configuration similar to that used for nonideal, simplified TI (time lens + dispersion) to create a TI system that leads to a focused image of the original event (i.e., as in an ideal TI system). This approach eliminates the bandwidth limitations of the previous microwave frequency-upshifting techniques, providing in fact the unparalleled design flexibility to achieve a desired frequency upshifting.

The GTSI effect can be interpreted as the time-domain equivalent of the well-known spatial self-imaging (Talbot) effect under point source illumination.[5] Using a method based on the GTSI phenomenon, one can achieve a focused compressed (or magnified) temporal image of an arbitrary periodic temporal signal by use of the simplified TI system shown in Fig. 1. First an ultrashort optical pulse is dispersed in a dispersive element (e.g., an optical fiber), which introduces total dispersion $\ddot{\beta}_1 L_1$ (where $\ddot{\beta}_1$ is the first-order dispersion coefficient of the fiber

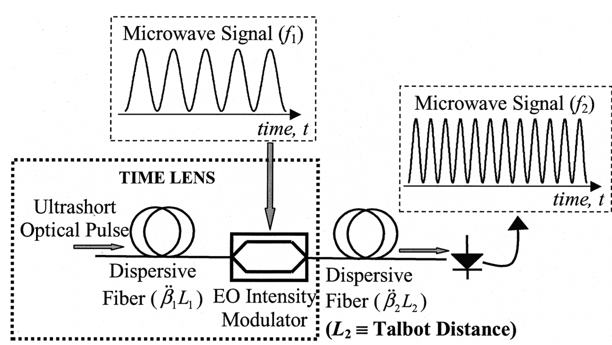

Fig. 1. Schematic of the proposed microwave frequency-shifting technique based on a general temporal self-imaging (Talbot) effect.

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and L_1 is the fiber length). The dispersed optical pulse is temporally modulated by a microwave periodic signal (e.g., a microwave tone) of repetition frequency f_1 by use of an intensity electro-optic (EO) modulator. In this way, the linear chirp of the optical pulse after dispersion is impressed onto the microwave signal. This mechanism is similar to that of a time lens operating over the microwave signal. The temporal aperture of the system (temporal window over which the TI system operates) is thus determined by the temporal duration of the chirped optical pulse at the output of the first dispersive line. According to the GTSI theory, if the optical signal after modulation (periodic optical signal under a finite-duration, slow temporal envelope) is dispersed through a suitable second dispersive line (total dispersion, $\ddot{\beta}_2 L_2$), then a focused temporal image of this input signal will be observed at the output of the system. This is true as long as the second dispersion satisfies the following condition[5]:

$$|\ddot{\beta}_2 L_2| = N \frac{|M_t|}{2\pi {f_1}^2}, \tag{1}$$

where N is an arbitrary positive integer ($N = 1, 2, 3, \ldots$), and M_t is the desired magnification factor of the TI system ($|M_t| = f_1/f_2$, where f_2 is the repetition frequency of the output signal):

$$M_t = 1 + (\ddot{\beta}_2 L_2 / \ddot{\beta}_1 L_1). \tag{2}$$

To achieve frequency upshifting ($f_2 > f_1$), one must configure the TI system such that $|M_t| < 1$, and, as a result, the two dispersive lines in the system must provide dispersions with opposite signs; see Eq. (2). For comparison, if the conventional TI approach were used instead, the system should be designed to ensure that $|\ddot{\beta}_2 L_2| \ll |M_t|/(2\pi {f_1}^2) \approx 1/(2\pi f_1 f_2)$.[3] As a result, one could increase the generated frequency only by reducing the amount of dispersion in the second dispersive element, i.e., by reducing the dispersion introduced by the first dispersive element (to keep the same temporal magnification factor). A reduction in the input dispersion directly translates into a reduction of the temporal aperture of the system. This typical trade-off between the bandwidth and the temporal aperture in a simplified TI system essentially determines the poor performance of these systems in terms of the maximum frequency that they can handle in practice. The undesired time–bandwidth trade-off of conventional systems is, however, eliminated in our proposed approach, in which the two features, time aperture and microwave bandwidth, can be freely optimized as independent parameters [Eqs. (1) and (2)]. Note that the unparalleled design flexibility provided by our technique is in part associated with the fact that there is a free parameter (N) in Eq. (1) that can be fixed at the designer's convenience; e.g., the dispersions in the system can be made as large as desired.

Figure 2 shows a schematic of our experimental setup. An erbium-doped fiber ring laser (EDFRL) was used as the optical pulse source. Passive mode locking of the laser was achieved through nonlinear polarization rotation in a unidirectional ring resonator.[6] This source was operated at a wavelength near 1550 nm and generated ≈1-ps optical pulses. The pulse repetition rate was set to 10 MHz by careful adjustment of the laser resonator length by a tunable delay line. Part of the laser radiation was coupled out by an optical coupler (C1) and, after detection by a photodetector (PD1) and proper RF amplification (RFA), it was used as a synchronization signal (Synch.) in the RF synthesizer (Synth.) and as triggering signal (Trigg.) in the sampling oscilloscope (Oscill.). The fiber laser pulses were coupled out by a second optical coupler (C2) and subsequently stretched by the first dispersive stage [dispersion-compensating fiber (DCF), providing a total dispersion $\ddot{\beta}_1 L_1 = +2153\ \mathrm{ps}^2$] to a time width of ≈9 ns (temporal aperture). After suitable polarization control with an optical polarizer (Pol.), the stretched pulses were temporally modulated in intensity by the amplified sinusoidal microwave voltage from the RF synthesizer by a Mach–Zehnder electro-optic modulator (Modul.). The optical signal after modulation was temporally compressed with a second dispersive stage [conventional telecommunication fiber (SMF-28)]. In our first set of experiments the SMF-28 fiber introduced a dispersion of $\ddot{\beta}_2 L_2 = -1722\ \mathrm{ps}^2$. According to Eq. (2), this dispersion should provide a magnification of $M_t = 0.2$, i.e., microwave frequency upshifting by $1/M_t = 5$. The microwave signal at the output of the second dispersive stage was extracted with a high-speed photodetector, PD2 (bandwidth of 50 GHz), and measured with a sampling oscilloscope (bandwidth of 50 GHz). Figure 3 shows the measured signals at the output of the second dispersive stage (output of the system) when frequency f_1 of the input tone was fixed at different values (always ~10 GHz) such as to satisfy Eq. (1) with N varying from 4 to 6 in increments of 0.5. Specifically, the input frequencies were fixed to $f_1 = 8.600$ GHz ($N = 4$) [Fig. 3(a)], $f_1 = 9.120$ GHz ($N = 4.5$) [Fig. 3(b)], $f_1 = 9.610$ GHz ($N = 5$) [Fig. 3(c)], $f_1 = 10.080$ GHz ($N = 5.5$) [Fig. 3(d)], $f_1 = 10.530$ GHz ($N = 6$) [Fig. 3(e)]. As evidenced by the results in Fig. 3, TI (frequency upshifting) is achieved only when the GTSI condition in Eq. (1) is satisfied with N being an exact integer. This is so for Figs. 3(a), 3(c), and 3(e). In these cases our system provided a focused temporal replica of the original tone compressed by

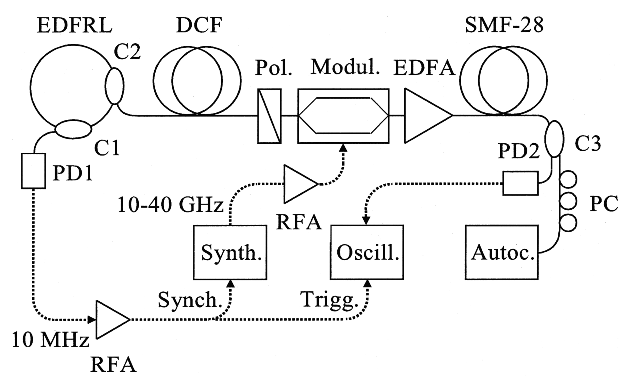

Fig. 2. Experimental setup: EDFA, erbium-doped fiber amplifier; C3, fiber coupler; PC, polarization controller; other notation defined in text.

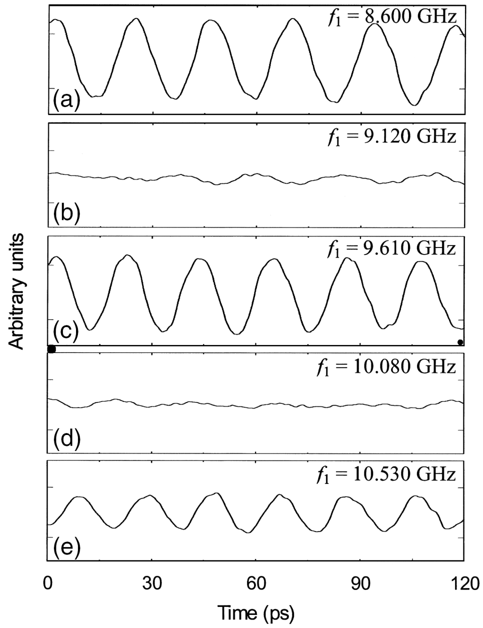

Fig. 3. Measured microwave signals at the output of the TI system (image magnification factor, $M_t = 0.2$) for several input modulation frequencies (f_1 near 10 GHz).

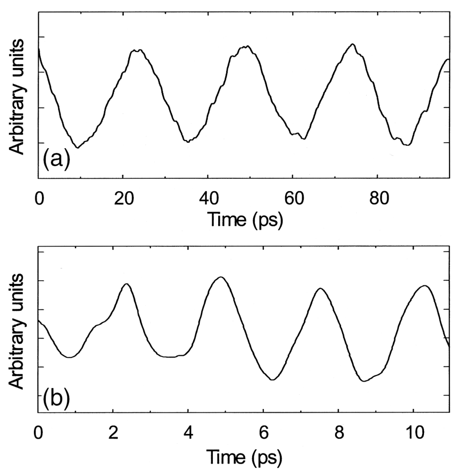

Fig. 4. Autocorrelation traces that correspond to the optical signals measured (a) before and (b) after the second dispersive stage when the TI system is configured for achieving $M_t = 0.113$, with $f_1 = 40$ GHz.

a factor of approximately $1/M_t = 5$; i.e., the desired microwave frequency upshifting by a factor of ≈ 5 was achieved. In particular, the frequencies of the output tones were (as estimated from Fourier analysis of the experimental curves) $f_2 = 42.820$ GHz [Fig. 3(a)], $f_2 \approx 47.874$ GHz [Fig. 3(c)], and $f_2 \approx 52.046$ GHz [Fig. 3(e)] (frequency upshifting by 4.979, 4.982, and 4.943, respectively). When N was not an integer, the amplitude of the output signal decreased drastically; see, for instance, the results in Figs. 3(b) and 3(d), where the microwave signals were practically filtered out by the TI system and only noise was received at the output. The situation when N is a noninteger would correspond to conventional TI operation (without exploiting the GTSI effect).[2,3] From these results it is obvious that the simplified TI system used in our experiments would be unable to generate frequencies as high as those demonstrated here (~50 GHz) unless the system were designed and configured to exploit the GTSI effect.

To illustrate further the capabilities of the proposed GTSI approach, we conducted a series of experiments to obtain radiation at frequencies well above 100 GHz. The results from one of these experiments are shown in Fig. 4. A larger frequency-upshifting factor was achieved now by use of a longer section of SMF-28 fiber as a second dispersive stage (total dispersion, $\ddot{\beta}_2 L_2 = -1910\ \mathrm{ps}^2$). According to Eq. (2), this system should provide a microwave frequency upshift by $1/M_t = 8.85$. In the experiment shown in Fig. 4 the input frequency was fixed to $f_1 = 40$ GHz to satisfy Eq. (1) with $N = 170$ (integer). Figure 4 shows the measured temporal signals at the input [Fig. 4(a)] and at the output [Fig. 4(b)] of the second dispersive stage (SMF-28 fiber). The signals in this experiment were measured with an optical autocorrelator (Autoc., Fig. 2). As expected, the output signal exhibited a frequency of $f_2 = 354.04$ GHz (as determined by Fourier analysis); i.e., the predicted frequency upshifting by 8.85 was achieved. For comparison, if conventional TI were used instead,[2] the maximum achievable frequency (for the same configuration and parameters as in our example) would be limited to ≈ 10 GHz.

In conclusion, a new approach to frequency upshifting of microwave signals has been proposed and experimentally demonstrated. The approach is based on time-domain processing in optical fibers and makes use of the GTSI phenomenon, providing an unparalleled design flexibility to increase the operation frequency of an arbitrary periodic microwave signal up to a desired value (limited only by the photodetector's bandwidth). The proposed technique could, for instance, be used to enhance the performance of current arbitrary waveform generation systems, easily leading to operation of these systems in the range of hundreds of gigahertz.

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