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Reconfigurable Linear Chirp Control in Photonic Generation of High-Frequency Microwave Pulses

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Abstract: A fiber-based approach for linear chirp control in optically-generated microwave pulses is proposed and demonstrated. Full linear chirp reconfigurability, including positive, negative and zero chirp rates, is achieved by tuning the relative delay in a fiber interferometer.

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1. Introduction

Pulse-based ultra-wideband (UWB) communication systems have recently attracted considerable attention for the next generation of wireless systems and radars [1]. Specifically a chirped microwave pulse with a central frequency up to tens of GHz and a high time-bandwidth product (TBWP) is often required in modern radar systems; these specifications are however normally out of the operational range of present electronic circuitry [2]. In this regard, photonic generation of microwave pulses is a promising approach [3,4]. This approach benefits from the extremely large bandwidths available in the optical domain. The main demonstrated approaches to photonic generation of microwave pulses include techniques based on frequency-domain pulse shaping, time-domain pulse shaping, direct space-to-time mapping, nonlinear frequency-to-time mapping (FTM) [3], and optical spectral shaping followed by linear FTM in a dispersive element [4].

All-fiber solutions for UWB microwave pulse generation are particularly interesting due to their full compatibility with fiber-optics systems and low insertion losses, among other advantages. Two basic all-fiber approaches to generate chirped microwave pulses which perform optical spectral shaping based on two delayed pulses interference and FTM [3,4] have been recently demonstrate to generate UWB chirped microwave pulses with frequency content ranging into the tens-of-GHz regime. In Ref. [3] (see Fig. 1.b.), a chirped microwave pulse was generated based on nonlinear FTM of an spectral interference (generated through a fiber interferometer) induced by third-order dispersion. The proposed system [3] would enable linear chirp control by properly tuning the relative time delay in the interferometer; however, this system can be tuned to generate different chirp rates only with the same chirp sign (e.g. a zero chirped microwave signal cannot be generated). In Ref. [4] (see Fig. 1.c.), the approach was based on chirped interference of which the spectral interference period increases or decreases with time. As illustrated in Fig. 1.c, the amount of chirp rate cannot be modified by time delay using this previous approach.

In this paper, we propose and demonstrate a novel and simple fiber-based approach (see schematic in Fig. 1.d.), firstly to add full reconfigurability to the two critical parameters that could not be tuned in previous works (central frequency in [3] and chirp in [4]) and secondly to add the capability of generating zero, positively and negatively chirped high-frequency microwave pulses by simply modifying the relative time delay in an interferometer. As illustrated in Fig. 1.d, we combine two basic mechanisms, namely chirped interference and nonlinear FTM, to achieve the desired linear reconfigurable chirp control. Chirped interference is performed by dispersion unbalance (DU) between the interferometer arms, which is practically realized by simply using two types of optical fibers with two different dispersion values in the interferometer arms. Nonlinear FTM is carried out in a chirped fiber Bragg grating (CFBG) that has both second- and third-order dispersion. This technique provides an unprecedented level of flexibility to tune both the central frequency and the linear chirp of the synthesized high-frequency microwave pulses; in particular, the proposed method allows us to generate any arbitrary amount of linear chirp in the synthesized microwave pulse, including positive, negative and zero chirp rates, by simply tuning the DU or relative delay in the interferometer.

2. Principle

The proposed system configuration is shown in Fig. 1.a. Nonlinear FTM is carried out based on second- and third-order dispersion ($\ddot{\Phi}_{01}$ and $\dddot{\Phi}_{01}$) in a CFBG. The desired chirped microwave pulse is generated by optical spectral shaping based on second-order DU ($\ddot{\Phi}_{02} - \ddot{\Phi}_{03}$) between the two arms of a fiber interferometer arms inducing a chirped spectral interference pattern. Notice that $\ddot{\Phi}_{02}$ and $\ddot{\Phi}_{03}$ refer to the amount of second-order dispersions corresponding to certain lengths of single-mode optical fibers, e.g. SMF and LEAF, respectively introduced in each of the interferometer arms. An approximate model for nonlinear FTM, according to a linear FTM scaling factor ($\ddot{\Phi}_{01}$) [5] that is frequency dependent for the nonlinear case ($\ddot{\Phi}_{01} + (1/3)\dddot{\Phi}_{01}\omega$), can be assumed, as defined by Eq. (1). Based on this approximate model the detected signal by a photodiode *i(t)*, can be written as in Eq. (2).

$$\omega = \left(1/\ddot{\Phi}_{01}\right)t - \left(\dddot{\Phi}_{01}/3\ddot{\Phi}_{01}^{3}\right)t^{2} \qquad (1)$$

$$i(t) = a(t).\left\{1+\cos\left[\left(\tau/\ddot{\Phi}_{01}\right)t + \left(\left[(\ddot{\Phi}_{02}-\ddot{\Phi}_{03})/2\ddot{\Phi}_{01}^{2}\right] - \left[\dddot{\Phi}_{01}\tau/3\ddot{\Phi}_{01}^{3}\right]\right)t^{2}\right]\right\} \qquad (2)$$

In Eq. (2), τ is the relative time delay between the two arms of the interferometer and *a(t)* is the input pulse envelope. Higher-order polynomial terms in Eqs. (1) and (2) have been neglected due to the very large amount of second-order dispersion introduced by the employed CFBG with respect to the input temporal pulse width. From the result in Eq. (2), it can be easily inferred that the central frequency f_c (Hz) and the linear chirp C (Hz/s) of the microwave pulse generated at the photodetector output can be expressed as in Eqs. (3) and (4):

$$f_c = (1/2\pi).\,\mathrm{mod}\left(\tau/\ddot{\Phi}_{01}\right),\; C = (1/2\pi).\,sign\left(\tau/\ddot{\Phi}_{01}\right).\,2\left((\ddot{\Phi}_{02}-\ddot{\Phi}_{03})/2\ddot{\Phi}_{01}^{2} - \dddot{\Phi}_{01}\tau/3\ddot{\Phi}_{01}^{3}\right) \qquad (3), (4)$$

Where *mod* denotes modulus and the function *sign* is defined as *sign(x)*=1 *for x*>0, 0 *for x*=0, -1 *for x*<0. According to Eq. (4), the linear chirp rate can be linearly controlled by simply tuning the relative time delay (see illustration in Fig 1.d). Eventually, we can linearly vary the frequency chirp rate from negative to positive values including the zero chirp. This is a fundamentally unique feature of our technique as compared with any of the previously proposed photonic methods for reconfigurable microwave pulse generation; in particular, a zero-chirp microwave pulse is obtained when the two chirp terms, one induced by nonlinear FTM ($-\dddot{\Phi}_{01}\tau/3\ddot{\Phi}_{01}^{3}$) and one induced by DU in the interferometer ($(\ddot{\Phi}_{02}-\ddot{\Phi}_{03})/2\ddot{\Phi}_{01}^{2}$), compensate each other.

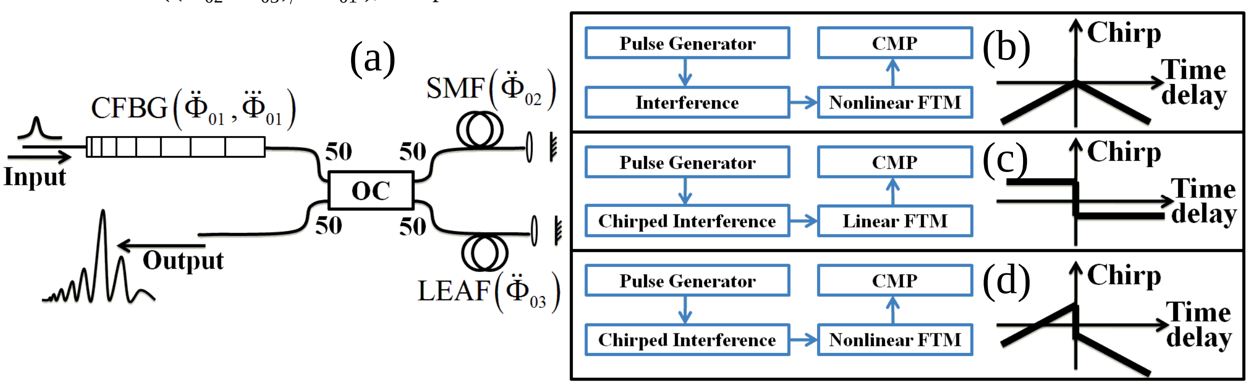

Fig.1. System configuration (a) and description of our proposed technique (d), which can be interpreted as a combination of two previously demonstrated basic mechanisms for chirp control (b) (from Ref. [3]) and ,(c) (from Ref. [4]). (OC: optical coupler, FTM: frequency-to-time mapping, CMP: chirped microwave pulse, SMF: single mode fiber SMF28, LEAF: single mode fiber LEAF)

3. Experiment and Simulation

Fig. 1.a shows an schematic of our experimental setup. As an input pulse, a subpicosecond Gaussian-like optical pulse with an effective (FWHM) bandwidth of 4.5nm at the central wavelength of 1550nm and repetition rate of 16.7MHz was generated using a passively mode-locked fiber laser. The second- and third-order dispersions of the employed CFBG are $\ddot{\Phi}_{01} = -2632\,ps^{2}$ and $\dddot{\Phi}_{01} = -18\,ps^{3}$ respectively. The second-order dispersion for 1m length of SMF and LEAF are $\ddot{\Phi}_{02} = -0.042\,ps^{2}$ and $\ddot{\Phi}_{03} = -0.010\,ps^{2}$ respectively. The output optical signal was captured by a high-speed (~30GHz) photodiode and the synthesized microwave waveform at the photodiode output was monitored with a sampling oscilloscope.

As anticipated by the theoretical analysis summarized above, for each central frequency of the generated microwave pulse, the effect of third-order dispersion is compensated for a certain amount of DU between the interferometer arms; based on this fact, we have designed the proof-of-concept experiments to achieve the zero chirp condition for some different central frequencies of the synthesized microwave pulse. In particular, we have introduced some different values of DU ($\ddot{\Phi}_{02} - \ddot{\Phi}_{03}$), by putting 2m, 20m, 50m and 180m lengths of the two selected types of single mode fibers, SMF28 and LEAF fiber, in each arm of the interferometer. According to the dispersion characteristics of the SMF and LEAF fibers and the employed CFBG, our numerical simulations revealed that the zero chirp condition happens at the following central frequencies: 450MHz for 2m, 8.4GHz for 20m, 21.1GHz for 50m and 63.5GHz for 180m. For each of these fiber lengths, the relative time delay was modified so that to tune the chirp and central frequency of the generated microwave signal, thus generating a broad range of central frequencies from 100MHz up to 26GHz. The results of experimental measurements for central frequency and chirp versus relative time delay for the different tested amounts of DU are shown in Fig. 2 (a) and (b). The corresponding simulation curves for central frequency and chirp versus time delay have also been superimposed in Fig. 2 (a) and (b). Experimental results show an excellent agreement with what we expect from simulations and the approximate theoretical model in Eq. (3) and (4), having proved the unique capability of our method for synthesizing high-frequency microwave pulses with zero chirp as well as with different amounts of positive and negative chirps. The generated microwave signal at three experimental measurement points of the curves shown in Fig. 2 (b) with three different chirp rates (positive, zero and negative) are shown in Fig. 2 (c), (d) and (e).

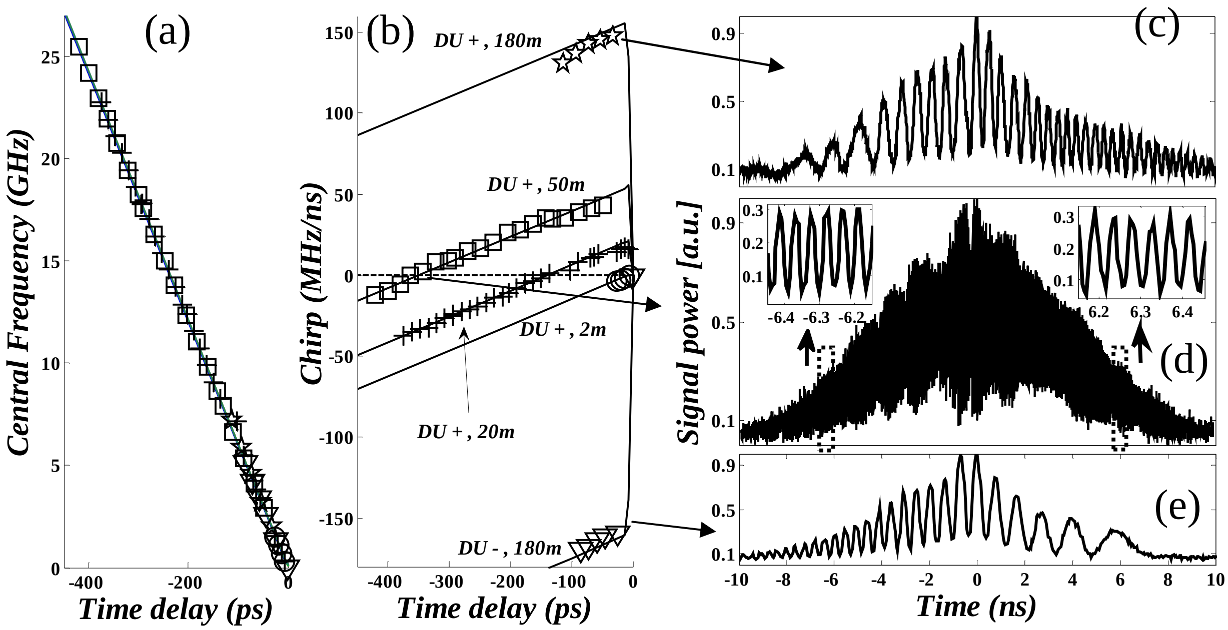

Fig. 2. Experimental (separate points) and simulation (solid curves) results for central frequency and chirp of the generated microwave signal as a function of the relative time delay in the interferometer for positive DU induced by SMF and LEAF fiber lengths of 2m, 20m, 50m, 180m and negative DU induced by 180m of SMF and LEAF fibers (a), (b) and three samples of experimental power waveform of the generated microwave pulses with f_c=1.8[GHz], C=+148[MHz/ns] (c), f_c=21.1[GHz], C=0 (d) and f_c=1.4[GHz], C= -159[MHz/ns] (e).

4. Conclusion

We proposed and experimentally demonstrated a new fiber-based approach for full linear chirp control in photonic generation of microwave pulses, enabling a bidirectional (positive, zero, and negative) frequency chirp rate sweep by simply varying the time delay in a two-arm interferometer. This linear sweep control has been achieved by combining nonlinear FTM (induced by the third-order dispersion of a linear temporal stretcher, e.g. CFBG) and DU between the interferometer arms, leading to a counteraction of the respective nonlinear responses (i.e. nonlinear FTM v.s. chirped spectral interference). Linear frequency sweeps of sinusoid microwave pulses were obtained with the central-frequency and the chirp-rate ranges of 25GHz and ±150 MHz/ns, respectively.

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