An Approach to Photonic Generation of High-Frequency Phase-Coded RF Pulses

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***Abstract*—A novel method to generate high-frequency phase-coded RF pulses using all-fiber components is proposed. The system consists of a mode-locked fiber laser (MLFL), a dispersive element, an unbalanced Mach–Zehnder interferometer (UMZI), an optical phase modulator (PM), and a photodetector (PD). The PM is incorporated in one arm of the UMZI. In the system, an ultrashort pulse generated by the MLFL is broadened and chirped after passing through the dispersive element, which is then sent to the UMZI, to get two time-delayed chirped pulses. By beating the time-delayed chirped pulses at the PD, an RF pulse with its frequency dependent on the time delay difference is obtained. The generated RF pulse can be phase coded if an encoding signal is applied to the PM. A theoretical model is presented which is verified by experiments. The generation of RF pulses with binary phase coding is also experimented.**

***Index Terms*—Microwave photonics, mode-locked fiber laser (MLFL), phase coding, phase modulation, RF signal generation.**

I. Introduction

OPTICAL generation of microwave and millimeter-wave (mm-wave) signals has been a topic of interest for many years, which offers a wide range of applications, such as radio-over-fiber networks, software-defined radio, antenna remoting, satellite communications, and optical sensing [1]. The generation of continuous-wave microwave or mm-wave signals based on optical heterodyne has been intensively investigated, and different approaches have been proposed [2], [3]. On the other hand, it is also desirable to generate pulsed RF signals for applications such as radar and wireless communications. In a modern radar system, for example, to increase the range resolution, pulse compression techniques are widely used. To achieve pulse compression, the radar pulses are usually chirped or phase-coded to increase the time-bandwidth product (TBWP) [4]. Pulsed RF signals can be generated in the electrical domain using either analog or digital electronics, but the frequency is usually limited to several gigahertz. To generate pulsed RF signals with a high frequency, optical techniques may be used. Spatial light modulator (SLM)-based pulse shaping techniques have been demonstrated to be a viable solution for the generation of high-frequency arbitrary RF waveforms, such as chirped or phase-coded RF pulses [5], [6]. The major difficulty associated with the SLM-based approaches is that the pulse shaping operation is implemented in free space, which makes the system bulky and complicated. High-frequency RF pulses can also be generated using pure fiber-optic components. Recently, Zeitouny *et al.* demonstrated an all-fiber system to generate linearly chirped RF pulses using an ultrashort pulse source and chirped fiber Bragg gratings (FBGs) [7].

In this letter, we propose a novel approach to generating phase-coded RF pulses using pure fiber-optic components. The system consists of a mode-locked fiber laser (MLFL), a dispersive element, an unbalanced Mach–Zehnder interferometer (UMZI), an optical phase modulator (PM), and a photodetector (PD). In the system, an ultrashort pulse generated by the MLFL is broadened and chirped after passing through the dispersive element, which is then sent to the UMZI. The optical PM is placed in one arm of the UMZI to perform phase encoding of the pulsed RF signal. At the output of the UMZI, two time-delayed chirped pulses are obtained. By beating the two time-delayed chirped pulses at the PD, a pulsed RF signal with its RF frequency determined by the time delay difference is generated. The generated RF pulse can be phase coded if an encoding signal is applied to the PM. A theoretical model is presented which is verified by experiments. The generation of RF pulses with binary phase coding is also experimentally demonstrated.

II. System Configuration and Theoretical Model

The schematic diagram of the proposed system is shown in Fig. 1. An ultrashort pulse generated by the MLFL is sent to the dispersive element. Theoretically, we can assume that the ultrashort pulse generated by the MLFL is a transform-limited Gaussian pulse, which is expressed as

$$E(t) = \exp\left(-t^2/\tau_0^2\right) \tag{1}$$

where τ_0 is the half width at $1/e$ maximum of the pulse. After experiencing chromatic dispersion in the dispersive element, the ultrashort pulse is broadened and chirped, which can be approximated as

$$E_D(t) = \exp(t^2/\tau^2)\exp\left[-jt^2/(2\ddot{\Phi})\right] \tag{2}$$

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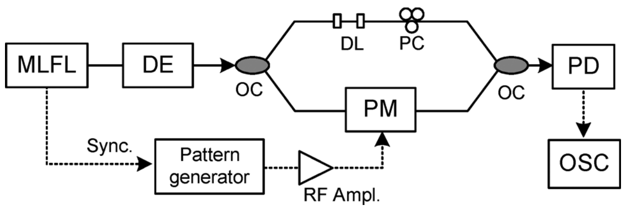

Fig. 1. Schematic diagram of the proposed system for the generation of phase-coded RF pulses. DE: dispersive element. OC: optical coupler. DL: delay line. PC: polarization controller. OSC: oscilloscope.

where τ is the pulsewidth after experiencing the dispersion, $\ddot{\Phi}$ is the first-order dispersion of the dispersive element. Here, we assume $|\ddot{\Phi}/\tau^2| \ll 1$, which means that the pulse duration of the ultrashort pulse from the MLFL is much smaller than that after experiencing the chromatic dispersion. This assumption is always true for subpicosecond pulses propagating in a few hundreds of meters of standard single-mode fiber (SSMF) [8]. The phase quadrature term in (2) shows that the pulse is linearly chirped.

The pulsewidth τ of the broadened and chirped pulse is given by [9]

$$\tau = \tau_0 \left(1 + \ddot{\Phi}^2/\tau_0^4\right)^{1/2} \approx |\ddot{\Phi}|/\tau_0. \tag{3}$$

The broadened and chirped pulse is then sent to the UMZI. At the output of the UMZI, the electrical field of the pulse is

$$E_{\text{out}}(t) = \left\{E_D(t-\Delta t) + E_D(t)\exp\left[j\Psi(t)\right]\right\}/2 \tag{4}$$

where Δt is the time delay difference between the two arms of the UMZI, and $\Psi(t)$ denotes the phase information introduced by the optical phase modulation.

Substituting the expression of $E_D(t)$ in (2) into (4), we have

$$\begin{aligned} E_{\text{out}}(t) = \Big\{&\exp\left[-(t-\Delta t)^2/\tau^2\right]\exp\left[-j(t-\Delta t)^2/(2\ddot{\Phi})\right] \\ &+\exp[-t^2/\tau^2]\exp\left[-jt^2/(2\ddot{\Phi})\right]\exp\left[j\Psi(t)\right]\Big\}\Big/2. \end{aligned} \tag{5}$$

The electric current at the output of the PD is proportional to the intensity of the input electrical field, which is given

$$\begin{aligned} I(t) &= \mathcal{R}\left|E_{\text{out}}(t)\right|^2 \\ &= \frac{1}{4}\mathcal{R}\exp\left[-2(t-\Delta t)^2/\tau^2\right] + \frac{1}{4}\mathcal{R}\exp[-2t^2/\tau^2] \\ &\quad + \frac{1}{2}\mathcal{R}\exp\left\{\left[-t^2-(t-\Delta t)^2\right]/\tau^2\right\} \\ &\quad \times\cos\left[(\Delta t)t/\ddot{\Phi} + \Psi(t) + \Delta t^2/(2\ddot{\Phi})\right] \end{aligned} \tag{6}$$

where $\mathcal{R}$ is the responsivity of the PD. It can be seen from (6) that the first and the second terms in the right-hand side of the equation are the low-frequency components, and the third term is the high-frequency component with a center frequency given

$$f_c = \Delta t/\left(2\pi|\ddot{\Phi}|\right). \tag{7}$$

It is shown that the carrier frequency of the generated RF pulse is determined by the time delay difference between the two arms of the UMZI for a given total chromatic dispersion in the system. Therefore, we can adjust the carrier frequency of the generated RF pulse by tuning the fiber delay line in the UMZI. In addition, it is shown in (6) that the phase information $\Psi(t)$ applied to the optical PM is transferred to the generated RF pulse. Thus, the generated RF pulse is phase coded.

The time aperture of the generated pulse T is given by the overlapping of the two delayed chirped optical pulses, which can be approximated by $T = \tau - \Delta t$. Since the bandwidth of the generated pulse B is limited by the carrier center frequency $B \leq f_c$ according to (3) and (7), the maximum available TBWP of the generated pulse can be approximated by

$$\text{TBWP} = T \cdot B \leq T \cdot f_c = |\ddot{\Phi}| f_c[1/\tau_0 - 2\pi f_c]. \tag{8}$$

It can be seen that the maximum available TBWP depends on the input optical pulsewidth τ_0, the dispersion value $|\ddot{\Phi}|$, and the center frequency f_c. To have a high f_c, the time delay difference Δt should be large, but a large Δt leads to a reduction in the pulse duration. To generate a pulse with a large TBWP, a solution is to increase $|\ddot{\Phi}|$. For example, for a given optical pulsewidth $\tau_0 = 210$ fs and center frequency $f_c = 50$ GHz (corresponding to $\Delta t = 0.47$ ns), a maximum TBWP of over 300 can be achieved when $|\ddot{\Phi}| = 1500$ ps^2.

III. Results

The experimental setup shown in Fig. 1 is implemented to demonstrate the proposed approach and to verify the given theoretical model. In the experiment, we use a passively mode-locked femtosecond pulse laser with a half width at $1/e$ maximum of 210 fs, which corresponds to a full-width at half-maximum of 350 fs, a repetition rate of 48.6 MHz, and an output power of 2.5 mW. A length of SSMF is employed as the dispersive element. A pattern generator, which is synchronized to the femtosecond pulse laser, is used to generate the phase encoding signal. The pulsed RF signal detected by the PD is monitored by an oscilloscope. Note that the optical pulse traveling in the SSMF will be distorted due to the nonlinear effects. To avoid the nonlinearity-induced distortions, an optical attenuator is inserted between the MLFL and the SSMF to reduce the power to the SSMF. We then compare the optical spectra before and after the SSMF. It is found that the spectra are almost identical except for some attenuation, which confirms that the propagation of the pulse through the SSMF is dominated by the chromatic dispersion.

First, we use 4-km SSMF as a dispersive element; the dispersion parameter $\ddot{\Phi}$ of the fiber is around 87.4 ps^2. The time delay difference Δt of the UMZI is set at 9.88 ps. The carrier frequency of the generated pulse is calculated to be 18 GHz. The waveform calculated by the theoretical model and the experimental RF waveform, both without phase modulation, are shown in Fig. 2(a) and (b), respectively. It can be seen from the figure that the two waveforms match very well, which verifies the theoretical model. Due to the limited bandwidth of the oscilloscope and the polarization mismatch within the UMZI, the visibility of the experimental waveform is slightly lower than that obtained based on the theoretical model. It is expected that the use of polarization-maintaining components in the system would improve the visibility of the generated RF signal. In the

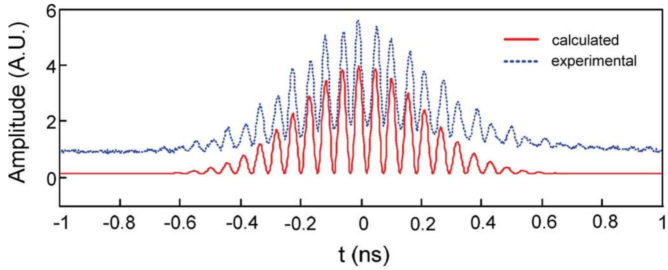

Fig. 2. Generation of 18-GHz RF pulse without phase modulation. Solid line: pulse obtained by the theoretical model. Dotted line: experimentally generated pulse.

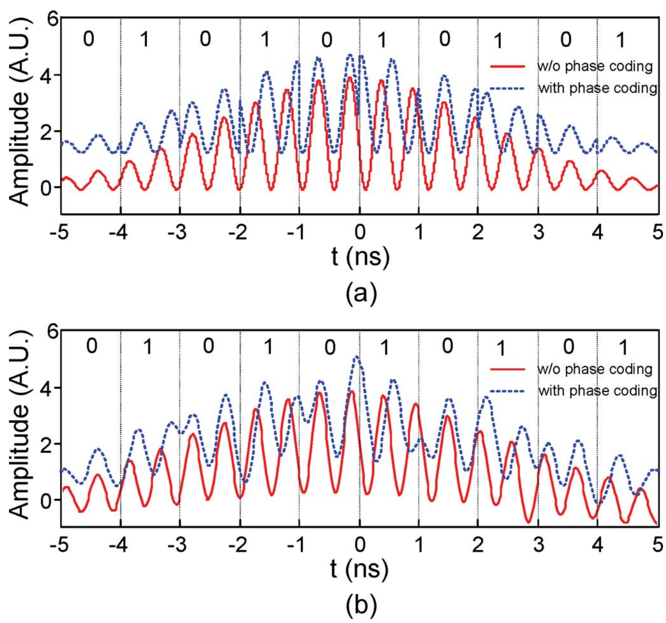

Fig. 3. Generation of 2-GHz RF pulse. (a) Calculated waveforms. (b) Experimental waveforms.

experiment, the maximum available TBWP, calculated by multiplying the measured pulsewidth and the center frequency, is about 6.8, which is close to the theoretical value of 7.3 calculated using (8). To increase the maximum TBWP, a dispersive element with a much greater dispersion must be used.

Then, we use 65-km SSMF as the dispersive element. The dispersion parameter $\ddot{\Phi}$ of the fiber is around 1420 ps^2 and the time delay difference Δt is about 17.8 ps. The carrier frequency of the generated pulse is calculated to be 2 GHz. A binary non-return-to-zero digital sequence with a data rate of 1 Gb/s, generated by a pattern generator and amplified by an RF amplifier, is applied to the PM. Fig. 3(a) shows the theoretical waveforms with and without phase encoding calculated according to (6). The experimental waveforms, with and without phase encoding are shown in Fig. 3(b), in which a bit "1" corresponds to a phase shift of around 120° and a bit "0" corresponds to a zero phase shift. The generated phase-coded signal matches well with the calculated phase-coded signal except for the waveforms at the bit edge, which is caused by the nonideal square waveform generated by the pattern generator. The phase shift value corresponding to bit "1" can be adjusted by controlling the power of the digital sequence to the PM.

Note that the proposed system can also generate other types of pulsed RF signals if the modulating signal applied to the optical PM is different. For example, a frequency-shift keying signal can be generated if a triangle waveform is applied to the PM. In the experiment, the amplitude of the generated pulse is around 15 mV, which is limited by the PD. To generate a signal with a higher amplitude, an RF amplifier may be incorporated into the system after the PD.

In the proposed scheme, the encoding codes are generated in the electrical domain using a pattern generator. For a real system, the codes may be generated using a state-of-the-art electronic circuit with a data rate up to 100 Gb/s. The center frequency of the generated RF signal can be in the microwave and mm-wave bands, with the maximum frequency limited only by the bandwidth of the PD. For a given pulsewidth and center frequency, the maximum TBWP is determined by the dispersion of the dispersive element. In the experiment, we use SSMF as the dispersive element. To reduce the size and to have a higher chromatic dispersion, a chirped FBG may be used [10].

IV. Conclusion

We have proposed and demonstrated a system to generate high-frequency phase-coded RF pulses using pure fiber-optic components. A theoretical model was derived, which was verified by the experiments. The key advantage of the approach is that the center frequency of the generated signal can be adjusted by changing the time delay difference in the UMZI. In addition, the system can be implemented using all-fiber components, which provides the potential for integration. The proposed approach provides a simple and effective solution for the generation of high-frequency phase-coded pulsed RF signals, for applications in pulse compression radar, fiber radio, and spread-spectrum communications systems.

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