Chirped Microwave Waveform Generation Using an Unbalanced Sagnac Loop

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Abstract: A chirped microwave pulse generation scheme based on self-phase modulation effect in an unbalance Sagnac loop is proposed. The generation of chirped microwave pulses with a bandwidth as large as 23 GHz is experimentally demonstrated.

OCIS codes: (060.2630) Frequency modulation; (120.5790) Sagnac effect; (060.5625) Radio frequency photonics

1. Introduction

Chirped microwave signal is extensively employed in modern radar systems to increase the detection range and improve the range resolution [1, 2]. In many radar applications, the center frequency and bandwidth of the chirped microwave pulse need to be tens of gigahertz. However, the frequency and bandwidth of signals generated by pure electronic circuits are severely limited due to the electronic bottleneck [3]. Owing to the inherent characteristics of high speed and broad bandwidth, various photonics-based methods have been proposed for chirped microwave signal generation [4-9]. Among all these methods, the method based on optical wavelength-to-time mapping attracts many attentions. In this method, the optical spectrum of a mode-locked laser (MLL) are first shaped by a Mach-Zehnder interferometer (MZI) or a Sagnac loop [4-7]. Then, a dispersive element such as a single mode fiber (SMF) or a chirped fiber Bragg grating (CFBG) is applied to map the optical spectrum into time domain. The system is easy to implement but it is hard to adjust the center frequency and bandwidth of the generated signal once the spectral shaper is selected. Chirped microwave signals can also be generated by beating a pre-chirped optical pulse with a CW light or beating two optical pulses with different chirps at a photodetector (PD) [8, 9]. In such systems, the optical signal should be split into two branches for independent operations before they are combined again. Thus, the phase irrelevance between the two optical branches would deteriorate the quality of the generated chirped microwave signal.

In this report, we present a novel method to generate chirped microwave waveforms based on self-phase modulation (SPM) effect in an unbalanced Sagnac loop. The main advantage of the proposed method is that, the optical signal processing are implement within the same physical channel, thus the system has a very good stability. Besides, both the bandwidth and temporal duration of the generated signal can be easily adjusted in the proposed system. In the experiment, the generation of chirped microwave pulses with a bandwidth as large as 23 GHz is demonstrated.

2. Principle

![Fig.1. Schematic of the proposed method. MLL: mode-locked laser; PC: polarization controller; OGF: optical Gauss filter; EDFA: erbium doped fiber amplifier; SMF: single-mode fiber; DCF: dispersion compensating fiber; PD: photo-detector.](image)

Fig.1 shows the schematic diagram of the proposed signal generator, which consists of a mode-locked laser (MLL), a polarization controllers (PC), an optical Gauss filter (OGF), a highly nonlinear fiber (HNLF) and a photo-detector (PD). The short optical pulse generated by the MLL is first filtered by an OGF to obtain a Gauss pulse shape. After amplified by an erbium doped fiber amplifier (EDFA), the optical pulse is sent to the unbalanced Sagnac loop via an
optical circular. The HNLF is placed inside the Sagnac loop, and the optical coupler in the Sagnac loop has a power ratio of 1:9. Mathematically, the optical fields of the pulses transmitting along the clockwise and the counterclockwise directions can be expressed as

\[ s_1(t) = E \exp(-\frac{t^2}{2\delta^2}) \exp(j\omega t) \]

\[ s_2(t) = 3E \exp(-\frac{t^2}{2\delta^2}) \exp(j\omega t) \]

where \( E \) is a constant, \( \delta \) is the pulse width at 1/e of the maximum amplitude, and \( \omega \) is the angular frequency of the optical carrier. After the optical pulses pass through the HNLF reversely, the outputs of the HNLF are

\[ y_1(t) = s_1(t) \exp(j\gamma L_{eff}) \] \[ \exp(j\omega t) = E \exp(-\frac{t^2}{2\delta^2}) \exp(j\gamma L_{eff} E^2 \exp(-\frac{t^2}{\delta^2})) \exp(j\omega t) \]

\[ y_2(t) = s_2(t) \exp(j\gamma L_{eff}) \] \[ \exp(j\omega t) = 3E \exp(-\frac{t^2}{2\delta^2}) \exp(j\gamma L_{eff} 9E^2 \exp(-\frac{t^2}{\delta^2})) \exp(j\omega t) \]

where \( L_{eff} \) is the effective length of the HNLF and \( \gamma \) is the nonlinear coefficient. When the optical pulses are combined again at the coupler, the combined optical field is

\[ y_3(t) = E_1 \exp(-\frac{t^2}{2\delta^2}) \] \[ \exp(j\gamma L_{eff} E^2 \exp(-\frac{t^2}{\delta^2})) + \exp(j\gamma L_{eff} 9E^2 \exp(-\frac{t^2}{\delta^2})) \exp(j\omega t) \]

where \( E_1 \) is another constant. When this optical signal is sent to a PD, the generated electrical current is

\[ i(t) = \Re \left[ y_3(t) \cdot y_3(t) \right] - \Re \left[ E_1^2 \exp(-\frac{t^2}{\delta^2})(2 + 2\cos[\phi(t)]) \right] \]

where

\[ \phi(t) = \gamma L_{eff} E^2 \left[ 9 \exp(-\frac{t^2}{\delta^2}) - \exp(-\frac{t^2}{\delta^2}) \right] = 8\gamma L_{eff} E^2 \exp(-\frac{t^2}{\delta^2}) = 8\gamma L_{eff} E^2 (1 - \frac{t^2}{\delta^2}) \]

\( \Re \) is the responsibility of the PD. According to Eq. (7), a chirped microwave waveform signal is generated and a linear chirp is achieved at the center of each pulse. The prominent feature of the proposed system is that the quasiquadratic phase difference between the counter propagating optical pulses is introduced in the same physical channel. Therefore, the system stability is greatly improved compared with the systems where separation and recombination of multiple channels are required. Besides, the bandwidth of the generated microwave signal can be tuned by changing the HNLF parameters or the input pulse power. To broaden the temporal duration of the generated microwave pulse, a span of dispersion compensation fiber (DCF) can be used before the PD to stretch the pulse width.

3. Experimental results and discussion

To verify the feasibility of the proposed system, an experiment is performed. In the experiment, a span of single mode fiber (SMF) is applied instead of the HNLF. The MLL (Calmar, FPL-03CFFSKY11) has a repetition rate of 10MHz. It is filtered by an OGF (Waveshaper 4000s) which has a 3-dB bandwidth of 8nm and a center wavelength of 1550nm. The pulse width after the OGF is around 1 ps. The average power of the optical pulse injected to the Sagnac loop is around 0 dBm. A PD with a bandwidth of 50 GHz is applied to implement optical-to-electrical conversion. The waveform of the generated microwave pulses is measured by a real-time oscilloscope (Keysight, DSAX93204A) with a sampling rate of 80 GSa/s.

Fig. 3 shows the waveforms of the generated chirped microwave pulses. In Fig. 3, the results are obtained when the parameters of the SMF and the DCF are (6 km, -1314 ps/nm), (6 km, -1656.7 ps/nm), (1.5 km, -1314 ps/nm) and (1.5 km, -1656.7 ps/nm), where \( (a, b) \) is the length of the SMF and \( b \) is the dispersion of the DCF. Table.1 shows the recovered instantaneous frequency and the pulse duration corresponding to the generated waveforms in Fig.3. As can be seen in Fig. 3 and Table. 1, the maximum bandwidth of the generated signal reach as large as 23 GHz (0-23 GHz). By changing the length of the SMF and the DCF, both the temporal duration and bandwidth of the generated signal can be adjusted in the established system. For example, when the length of the SMF is 6 km and the
dispersion of the DCF changes from -1314 ps/nm to -1656.7 ps/nm, the temporal duration increases from 6 ns to 6.5 ns while the bandwidth decreases from 23 GHz (0-23 GHz) to 15 GHz (0-15 GHz). When the dispersion of the DCF is fixed to be -1314ps/nm and the length of the SMF changes from 6 km to 1.5 km (i.e., the SPM effect is weakened), the signal bandwidth decreases from 23 GHz (0-23 GHz) to 4.9 GHz (0.1-5 GHz).

Fig.2. Waveform and instantaneous frequency of the generated chirped microwave pulses when changing the length of the SMF and the dispersion of the DCF. (a), (c), (e), (g) are the temporal waveforms, (b), (d), (f), (h) are the corresponding instantaneous frequencies.

<table>
<thead>
<tr>
<th>SMF (km)</th>
<th>DCF dispersion (ps/nm)</th>
<th>instantaneous frequency (GHz)</th>
<th>pulse duration (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>-1314</td>
<td>0-23</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>-1656.7</td>
<td>0-15</td>
<td>6.5</td>
</tr>
<tr>
<td>1.5</td>
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<td>1.5</td>
<td>-1656.7</td>
<td>0.1-3.4</td>
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</tr>
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</table>

4. Conclusion and acknowledgment

A chirped microwave waveform generation scheme has been proposed based on SPM effect in an unbalance Sagnac loop. The proposed system has a compact structure, and the bandwidth and temporal duration of the generated chirped microwave pulses can be easily adjusted. A proof-of-concept experiment is performed and the results can verify the feasibility of the proposed system.

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6. References