High-Resolution Microwave Frequency Measurement Based on Temporal Channelization Using a Mode-locked Laser

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Abstract — High resolution microwave frequency measurement based on temporal channelization using a mode-locked laser is proposed and demonstrated. In the proposed system, a highly chirped optical pulse is modulated by a microwave signal with its frequency to be measured. The temporal microwave waveform is then mapped to the spectral domain thanks to dispersive Fourier transformation in a dispersive fiber. An optical channelizer is then employed to filter the spectrum, which is equivalent to performing temporal sampling of the temporal waveform. The microwave signal can then be reconstructed and its spectral distribution can be analyzed. Our method features greatly improved measurement resolution, which is more than two orders of magnitude higher than that based on the direct use of an optical channelizer. To evaluate the proposed technique, frequency measurement of a single-tone and a two-tone microwave signals is demonstrated. A measurement resolution as high as 200 MHz is achieved using an optical channelizer with 25-GHz channel spacing.

Index Terms — Channelizer, chirped pulse, dispersion, frequency measurement, microwave photonics.

I. INTRODUCTION

Real-time microwave frequency measurement is of critical importance for numerous applications, such as electronic warfare, radars and ultra wideband wireless communications [1]. For microwave frequency measurement, it is usually required that the system can provide wideband and high-speed operation with high resolution. It is also required that the system can measure microwave signals with multiple carrier frequencies.

Due to the distinct advantages over electronic techniques, such as large bandwidth, low loss, small size and immunity to electromagnetic interference, photonically assisted microwave frequency measurement has been a topic of interest recently [2-4]. For example, the frequency of a microwave signal can be measured by power monitoring based on frequency-to-intensity mapping in a dispersive element where a unique relationship between the microwave frequency and the optical power is established [2]. While this technique offers good measurement resolution (<200 MHz), it has difficulty in measuring a microwave signal with multiple frequency components. Techniques for instantaneous microwave frequency measurement with the capability to measure a microwave signal with multiple frequencies have also been proposed. These techniques are mainly implemented using an optical spectral channelizer [3-4]. Fig. 1(a) shows a conceptual diagram of a microwave frequency measurement system using an optical spectral channelizer. A microwave signal with unknown frequencies is modulated on a single-wavelength optical carrier at an electro-optical modulator (EOM). An optical channelizer followed by an array of low-speed photodetectors (PDs) is then used to sample the spectrum of modulated optical signal. The output of a particular channel corresponds to a particular microwave frequency. Therefore, frequency distribution can be measured. The measurement resolution, however, is determined by the channel spacing, which is usually low (>10 GHz). Numerous efforts have been made to increase the resolution [3-4], but the channel spacing is still large, usually greater than 1 GHz, which is too coarse for accurate frequency measurement. It was reported recently that by using a multi-wavelength optical source and an additional channelizer, a measurement resolution that is higher than the channel spacing can be obtained [5]. However, precise spectral alignment is needed, which makes the system complicated and costly.

In this paper, we propose and demonstrate a photonically assisted technique to achieve real-time microwave frequency measurement based on temporal channelization using a mode-locked laser. Thanks to the time-to-wavelength mapping in a dispersive element, a temporal microwave waveform which is
modulated on a chirped optical pulse is mapped to the spectral domain. A spectrum which has a shape that is identical to the temporal shape of the microwave signal is obtained. An optical channelizer is then employed to filter the spectrum, which is equivalently to sampling the temporal waveform. The microwave waveform is then reconstructed and its spectral distribution can be analyzed. Compared with the frequency measurement based on directly use of an optical channelizer, the proposed temporal channelization technique can provide an improved frequency measurement resolution, which is more than two orders of magnitude higher. The proposed technique is experimentally evaluated. A measurement resolution as high as 200 MHz is achieved using an optical channelizer with 25-GHz channel spacing.

II. PRINCIPLE

The proposed system is shown in Fig. 1(b). An ultrashort (femtosecond) optical pulse train, generated by a mode-locked laser, is sent to a dispersive element which is a length of dispersion compensating fiber (DCF). The pulse at the output of the DCF is temporally stretched and frequency chirped. Thanks to the dispersive Fourier transformation (OFT) \cite{6}, the temporally stretched pulse has a shape that is a mirrored version of its optical spectrum. The wavelength-to-time mapping relationship is given by

\[ t \propto D \times \lambda \]  

(1)

where \( D \) (ps/nm) is the group velocity dispersion (GVD) of the dispersive element. The OFT technique enables pulse-by-pulse spectroscopic measurement. Fast dynamic phenomena that are encoded in the optical spectrum can now be acquired in the time domain, which can find a diverse range of applications where fast real-time operations are needed \cite{7}.

The chirped optical pulse from the DCF is then modulated by a microwave signal with its frequency distribution to be measured. Due to the same mapping relationship in (1), the temporal microwave waveform is mapped to the spectral domain, with the spectrum having a shape that is a scaled version of its optical spectrum. Thus, the microwave signal is reconstructed, and its spectral distribution can be analyzed.

Let \( \Delta \lambda \) be the channel spacing of the optical channelizer, the equivalent temporal sampling rate is given by

\[ S = \frac{1}{D \times \Delta \lambda} \]  

(2)

The effective frequency measurement resolution, \( \Delta f \), is reversely proportional to the time window of the system, which is given by

\[ \Delta f = \frac{1}{T} - \frac{1}{B \times D} \]  

(3)

where \( T \) is the time window, which is defined as the duration when temporal sampling occurs, and \( B \) is the spectral bandwidth of the optical pulse. According to (2), by properly selecting the dispersion, the proposed frequency measurement technique can have a high temporal sampling rate (large measurement bandwidth). Moreover, since an ultrashort optical pulse usually has a broad spectral bandwidth (tens of nm or even larger), the technique offers high measurement resolution, which is independent of the channel spacing.

III. EXPERIMENT

To evaluate the proposed technique, two experiments are implemented based on the setup shown in Figure 1(b). A passively mode-locked laser is employed as the optical source to generate a transform-limited Gaussian-like pulse. The ultrashort optical pulse has a full-width at half-maximum (FWHM) of 550 fs, a 10-dB spectral bandwidth of 15 nm and a central wavelength of 1558.3 nm. A DCF with a GVD of -339 ps/nm is used to temporally stretch and frequency-chirp the ultrashort optical pulse to achieve the DFT. The optical pulse at the output of the DCF is measured in the spectral domain and the time domain, with the results shown in Fig. 2(a) and (b). The shapes are identical, which validates the linear frequency-to-time mapping given in (1).

Fig. 2. Measurement of the temporally stretched optical pulse in (a) the spectral domain and (b) the time domain.

The chirped optical pulse is then modulated by a microwave signal with its spectrum to be measured at a Mach-Zehnder modulator, which is biased at the quadrature (linear transmission) point. The modulated optical pulse is then sent to an optical channelizer for spectrum sampling. Again, due to the frequency-to-time mapping, the spectral sampling is equivalent to temporal sampling. Thus, the temporal waveform is sampled in the spectral domain using an optical channelizer. In the proof-of-concept experiment, the optical channelizer is a programmable optical spectral filter, which is configured to have 60 channels with 25-GHz channel spacing. An optical spectrum analyzer is used to measure the spectrum at the output of the channelizer. The output power of each channel is calculated by integrating the measured optical spectrum.
In the first experiment, the frequency measurement of a single-tone microwave signal is demonstrated. The temporally stretched optical pulse is modulated by a 3.06 GHz microwave signal. Fig. 3(a) shows the modulated optical pulse at the output of the modulator. The inset shows the single-tone microwave signal. Thanks to the DFT, its spectrum maps the temporal waveform, as shown in Fig. 3(b). The spectral response of the optical channelizer is also shown as dashed line. Fig. 3(c) shows the output power from each channel, which is normalized using the envelope of the pulse spectrum. It can be seen that the reconstructed microwave signal matches well with the original single-tone modulation signal. The Fourier transform of the measured waveform was shown in Fig. 3(d), which clearly shows that the modulating signal has a frequency of 3.09 GHz. The measurement error is as small as 30 MHz, which is mainly due to the limited time window.

Then, the frequency measurement of a two-tone microwave signal is demonstrated. The microwave modulation signal has two carrier frequencies at 0.81 and 1.42 GHz. The measured results are shown in Fig. 4. Again, a good agreement between the measured waveform and the original modulation signal is obtained. The Fourier transform clearly shows that modulating signal has two frequencies at 0.75 and 1.47 GHz, confirming the capability of measuring multiple frequencies.

According to (3), the system has a measurement resolution of ~200 MHz, which is more than two orders of magnitude higher than the value of the channel spacing. By using a mode-locked laser with a wider bandwidth, a higher resolution would be achieved. Since the measurement resolution is independent of the channel spacing, any standard optical channelizer, such as a wavelength division multiplexer (WDM), can be used to perform instantaneous microwave frequency measurement with high resolution. To increase the frequency measurement range, a dispersive element with a smaller value of dispersion is required. However, less dispersion causes a shorter time window. Therefore there is a fundamental trade-off between the frequency measurement range and resolution. Note that by calibrating the modulation process, the amplitudes of the frequency components can be also measured, making the system more practical.

IV. CONCLUSION

We have proposed and experimentally demonstrated a novel technique to measure the instantaneous frequency of a microwave signal based on temporal channelization. The temporal waveform was mapped to the spectrum, which was then sampled by an optical channelizer. The microwave waveform was reconstructed by using the sampled spectrum and the spectral distribution of the microwave signal was obtained by Fourier transform.

REFERENCES