Ultrahigh-Resolution Photonic-Assisted Microwave Frequency Identification Based on Temporal Channelization

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***Abstract*—Real-time ultrahigh-resolution microwave frequency identification is paramount for widespread applications, such as communications, radar, and electronic warfare. Photonics-assisted microwave frequency identification can be achieved using an optical channelizer. While this technique enables simultaneous measurement of multiple frequencies, it has poor measurement resolution due to the large channel spacing, which is usually greater than 1 GHz. Here, we introduce a new channelizer-based microwave frequency measurement technique that offers nearly 500 times higher spectral resolution. This method employs largely dispersed broadband optical pulses to encode the time-domain characteristics of the modulating signal to the optical spectral domain. An optical channelizer is employed to slice the spectrum, which is equivalent to performing temporal sampling of the time-domain waveform. The unknown microwave signal is then reconstructed and its spectral distribution is analyzed by a digital processor. To evaluate the proposed technique, frequency measurements of a single-tone, a multiple-tone, and a frequency-hopping microwave signal are demonstrated. A measurement resolution as high as 55 MHz is achieved using an optical channelizer with a channel spacing of 25 GHz.**

***Index Terms*—Channelizer, chirped pulse, dispersive Fourier transformation, frequency measurement, microwave photonics, sampling.**

I. Introduction

INSTANTANEOUS microwave frequency identification (IMFI) is of critical importance for demanding scientific, industrial, and defense applications such as cosmology [1], wireless communications [2], radar [3], and electronic warfare [4], [5]. The key requirements for IMFI include high speed, wide bandwidth, and high measurement resolution. The capability of measuring microwave signals with multiple frequencies is also an important requirement for practical applications. While conventional electronic solutions can achieve a high measurement resolution and large dynamic range [6], the frequency measurement range is very limited and the measurement speed is low due to the electronic bottleneck.

Due to the distinct advantages offered by photonics, microwave frequency measurement based on photonic techniques has been considered a promising solution that can provide IMFI with broader bandwidth and higher speed [7]–[9]. Extensive investigations have been performed to find photonics-assisted frequency measurement solutions recently [10]–[19]. One of the most commonly used techniques based on photonics is to measure the microwave frequency by power monitoring based on frequency-to-intensity mapping in a dispersive element where a unique relationship between the microwave frequency and the optical or microwave power is established [10]–[14]. While this technique offers good frequency measurement resolution, usually smaller than 200 MHz, it falls short in measuring a microwave signal with multiple frequency components.

To achieve multiple microwave frequency measurement, an optical channelizer is usually used to map different frequency components into different spaces (channels). An optical channelizer can be implemented using a Fabry–Perot etalon [15], [16], a diffraction grating [17], an arrayed-waveguide grating (AWG) [18], or an array of parallel phase-shifted fiber Bragg gratings (FBGs) [19]. Fig. 1(a) shows a conceptual diagram of a channelizer-based IMFI system. An incoming microwave signal is modulated on an optical carrier from a laser diode (LD) at an electrooptic modulator (EOM) and the microwave signal is up-converted to the optical domain, which is then de-multiplexed at an optical channelizer. Therefore, the spectral distribution of the microwave signal can be determined directly from the sampled optical spectrum at the output of the optical channelizer. The key limitation of using an optical channelizer for IMFI is the poor measurement resolution due to large channel spacing of an optical channelizer, usually greater than 1 GHz [17], [18]. The measurement resolution may be improved by using a multi-wavelength optical source and a second optical channelizer [20], [21], but the system complexity is significantly increased as a precise spectral alignment is needed.

In this paper, we propose and demonstrate a new channelizer-based method to implement IMFI that offers nearly 500 times higher frequency measurement resolution than the channel spacing. The fundamental of the approach is to encode a temporal modulating signal to the spectral domain using a dispersive element with large group-velocity dispersion (GVD). Due to the linear frequency-to-time mapping in a dispersed optical pulse, a pulse spectrum that has an identical shape as the

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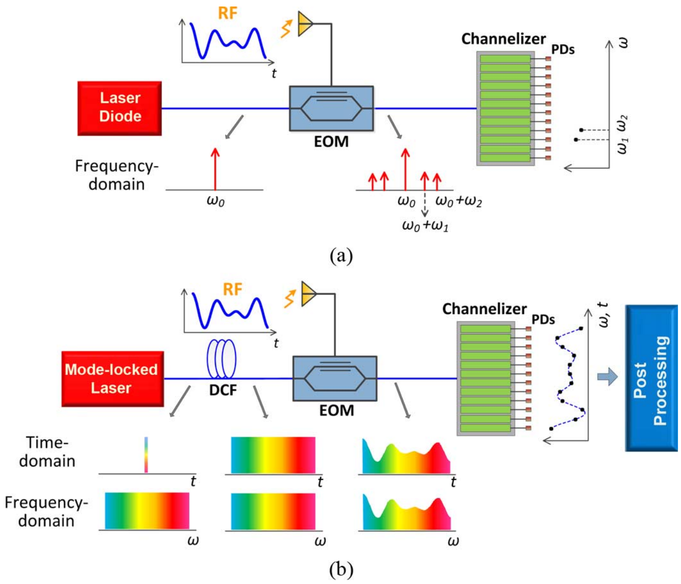


Fig. 1. Comparison between conventional optical-channelizer-based IMFI and our proposed IMFI-TeCh. (a) Conventional IMFI uses a single-wavelength continuous-wave optical carrier. (b) Conceptual diagram of the proposed IMFI-TeCh using a mode-locked laser. Electrooptic modulator: EOM; photodetector: PD; dispersion compensation fiber: DCF.

instantaneous temporal waveform is obtained. The temporal sampling is then equivalently performed in the spectral domain using an optical channelizer. The sampled output is detected using a low-bandwidth detector array and then analyzed using a digital processor and the spectral distribution of the temporal signal is obtained in real time from a Fourier transform analysis. Some preliminary results have been obtained [22]. In this paper, more experimental results are provided and a comprehensive analysis of the system performance is presented. Compared with frequency measurement using an optical channelizer for direct spectrum sampling [15]–[19], the proposed technique can provide a significantly improved frequency measurement resolution.

This paper is structured as follows. Section II describes the operation principle of the microwave frequency measurement technique based on temporal channelization. The proposed approach is evaluated experimentally with the results presented in Section III. Frequency measurements of a single-tone, a multiple-tone, and a frequency-hopping microwave signal are experimentally demonstrated. Further enhancement of the frequency measurement resolution by nonlinear optical spectrum broadening is also reported. In Section IV, discussions on key design parameters, as well as their inter-relations are presented. A conclusion is drawn in Section V.

II. Principle

The concept of the proposed microwave frequency measurement technique, which we refer to as the instantaneous microwave frequency identification based on temporal channelization (IMFI-TeCh), is shown in Fig. 1(b). A transform-limited ultrashort optical pulse, $a(t)$, generated from a mode-locked laser, is sent to a dispersive element, where it is temporally stretched and spectrally dispersed. Under the temporal Fraunhofer condition, $\ddot{\Phi}/(\Delta t)^2 \gg 1$, where $\ddot{\Phi}$ (in ps^2/rad) is the GVD of the dispersive element and Δt is the temporal pulsewidth, the temporally stretched pulse can be expressed as [23]

$$b(t) = a(t) \otimes h(t) \propto \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right) \times \int_{-\infty}^{+\infty} a(\tau)\exp\left(-j\tau\frac{t}{\ddot{\Phi}}\right)d\tau \propto \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right)A\left(\omega = \frac{1}{\ddot{\Phi}}\right) \quad (1)$$

where $h(t) \propto \exp(j\pi t^2/2\ddot{\Phi})$ is the impulse response of the dispersive element, and $A(\omega)$ is the Fourier transform of the input optical pulse $a(t)$. It can be seen that, neglecting the nonlinear optical effects in the dispersive element, the temporally stretched optical pulse has a spectrum with a shape that is a scaled version of the temporal waveform thanks to the dispersive Fourier transformation [23], [24]. The frequency-to-time mapping relationship is given by $\omega = t/\ddot{\Phi}$. The dispersive Fourier transformation technique has been successfully applied in a diverse range of applications [25] such as real-time pulse-by-pulse spectroscopic measurement [26], [27], temporal waveform generation [28], [29], and time-domain spectral shaping [30], [31].

A microwave signal $s(t)$ with its frequency distribution to be measured is then applied to an EOM, as shown in Fig. 1(b). Due to the one-to-one mapping between time and spectrum, the optical spectrum of the stretched pulse is also modulated by a scaled version of the microwave signal. Under linear small-signal modulation condition, if the frequency bandwidth of the microwave signal, $\Delta\omega_s$, satisfies the condition given by $\Delta\omega_s^2 \ll 8\pi/\ddot{\Phi}$[31], the spectrum of the modulated optical signal is then given by

$$C(\omega) \propto A(\omega)\exp\left(j\frac{\ddot{\Phi}}{2}\omega^2\right)s(t = \ddot{\Phi}\omega) \quad (2)$$

which indicates that the modulating signal is directly encoded into the amplitude of the spectrum of the modulated optical pulse—a process called time-domain spectral shaping [30], [31]. This is the key feature of this technique, which enables the equivalent sampling of the temporal waveform in the spectral domain using an optical channelizer. Let Ω be the channel spacing of the optical channelizer, the equivalent temporal sampling rate is then given by

$$R_{\text{samp}} = \frac{1}{\Omega \times \ddot{\Phi}}. \quad (3)$$

Based on the Shannon-Nyquist sampling theorem, to reconstruct a temporal signal without losing any information, the sampling rate must be at least two times the bandwidth of the microwave signal to be measured. Thus, the microwave signal can be reconstructed if the sampling rate is high enough, and its frequency distribution can be obtained by the Fourier transform analysis in a post digital signal processor.

The effective frequency measurement resolution, δf, is determined by the full-width at half-maximum (FWHM) bandwidth of the sidebands in the Fourier domain, which is reversely proportional to the time duration of the temporally stretched optical pulse and is given by

$$\delta f = \frac{1}{T} = \frac{1}{\Delta\omega_{\mathrm{opt}} \times \ddot{\Phi}} \tag{4}$$

where T is the width of the time window, which is defined as the total temporal duration in which the temporal sampling occurs, and $\Delta\omega_{\mathrm{opt}}$ is the spectral bandwidth of the optical pulse. Since an ultrashort optical pulse usually has a broad spectral bandwidth (several terahertz or even larger), the proposed temporal channelization technique can offer a much higher frequency measurement resolution (tens of megahertz), which is independent of the channel spacing, than an optical channelizer [15]–[19]. Moreover, the proposed IMFI-TeCh technique enables pulse-by-pulse spectroscopic measurement, and thus the update rate for the frequency measurement is identical to the repetition rate of the mode-locked laser source, which usually varies from tens of megahertz to several gigahertz. A comprehensive discussion on the design of the system and the impact on the measurement performance is presented in Section IV.

III. Experiment

To evaluate the proposed IMFI-TeCh technique, we constructed the apparatus shown in Fig. 1(b). A passively mode-locked fiber laser source is employed to generate a transform-limited Gaussian-like pulse train with a repetition rate of 48.6 MHz centered at 192.52 THz (1558.3 nm). The ultrashort optical pulse in the pulse train has an FWHM temporal width of 550 fs, and an FWHM spectral bandwidth of 1 THz (8 nm). A dispersion compensating fiber (DCF) with a GVD of $\ddot{\Phi} = 431.6$ ps^2/rad is used as the dispersive element to temporally stretch the ultrashort optical pulse for achieving the dispersive Fourier transformation. The stretched optical pulse at the output of the DCF is measured in both the spectral domain and the time domain, with the results shown in Fig. 2(a) and (b), respectively. It can be seen that the one-to-one mapping relation between frequency and time confirms the dispersive Fourier transformation given by (1). A slight distortion is observed in the stretched temporal waveform due to the high-order dispersion induced nonlinear frequency-to-time mapping in the DCF over the broadband spectrum [32]. The nonlinear mapping can be avoided by using a linearly chirped fiber Bragg grating (LCFBG) as the dispersive element, in which the high-order dispersion is negligible. In this work, however, the nonlinear mapping is corrected by calibrating the acquired data in the post-processing process [33].

The stretched optical pulse is then modulated by a microwave signal at a Mach–Zehnder modulator (MZM). The MZM is biased at the quadrature point, thus under the small-signal modulation condition ($<$ 5 dBm), the temporal microwave waveform is linearly modulated on the spectrum of the optical pulse. The modulated optical pulse is then sent to an optical channelizer for spectral filtering, which is equivalent to temporal sampling the microwave signal due to the frequency-to-time mapping relation. The powers at the outputs of the channels are measured and constitute the sampled version of the microwave signal under test. In the proof-of-concept experiments, the optical channelizer is a programmable optical spectral filter (Finisar WaveShaper 4000S), which can be configured to have up to 200 channels with a channel spacing of 25 GHz within a spectral range from 1527.5 to 1567.5 nm. An optical spectrum analyzer is then used to measure the filtered spectrum at the output of the channelizer. The output power of each channel is calculated by integrating the measured optical power spectrum within the channel. A sampled microwave signal representing the original temporal waveform is then obtained, which is finally sent to a post-processing module to perform Fourier transform analysis.

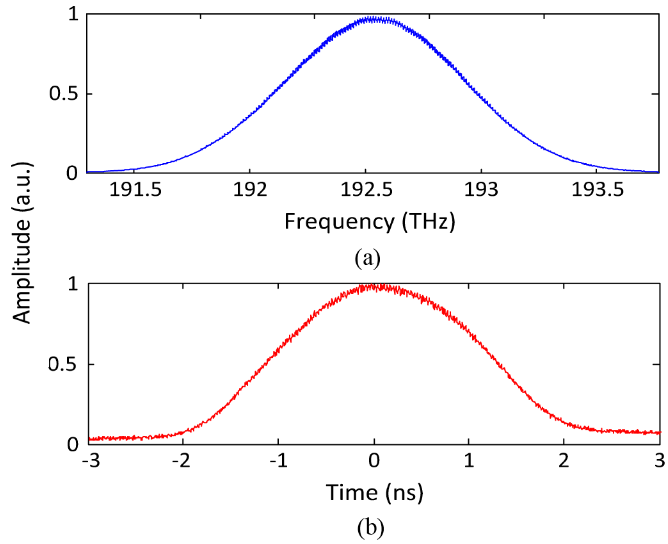
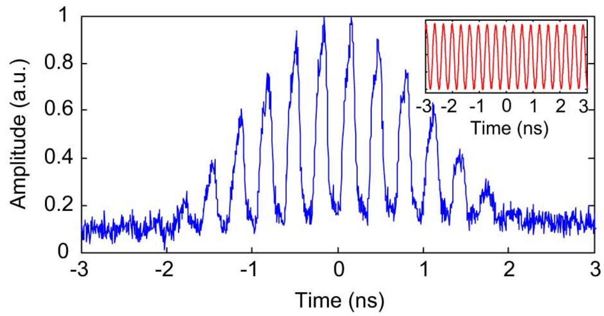


Fig. 2. Measurement of the temporally stretched optical pulse in the: (a) spectral domain and (b) time domain.

In the following, the employment of the proposed system to measure the frequency distribution of a single-tone, a multiple-tone, and a frequency-hopping microwave signal will be presented.

A. Measurement of a Single-Tone Microwave Signal

To demonstrate the proposed IMFI-TeCh technique, the frequency measurement of a single-tone microwave signal is first implemented. The microwave signal under test, which has a single carrier frequency of 3.06 GHz, is used to modulate the temporally stretched optical pulse. The modulated pulse is measured in both the time domain using a high-speed real-time oscilloscope and the spectral domain using an optical spectrum analyzer, with the results shown in Fig. 3(a) and (b), respectively. As can be seen, the shape of the spectrum of the modulated optical pulse is a scaled version of the temporal waveform, which confirms the dispersive Fourier transformation and time-domain spectral shaping. An optical channelizer having 60 channels with a channel spacing of 25 GHz is used to slice the spectrum of the modulated optical pulse. Fig. 3(c) shows the output powers from the channels of the optical channelizer, which is normalized against the Gaussian-shape envelop of the pulse spectrum. A sampled version of the microwave signal



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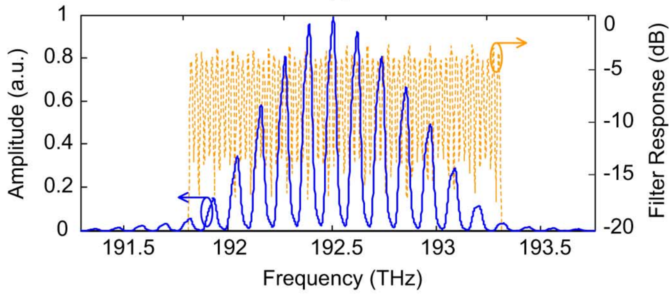

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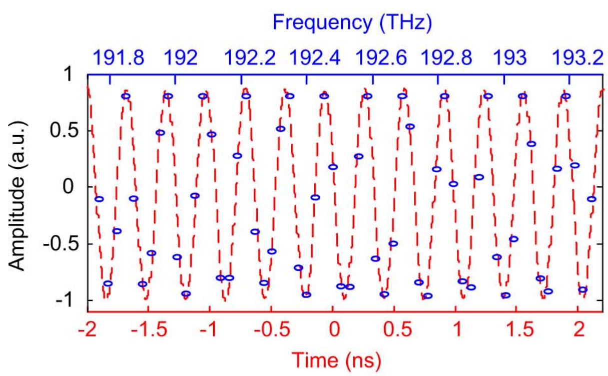

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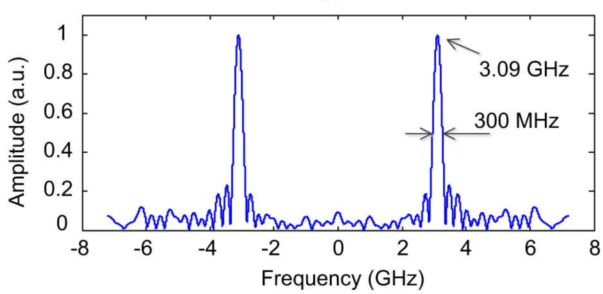


(d)

Fig. 3. Frequency measurement of a single-tone microwave signal. (a) Modulated optical pulse at the output of the MZM. The inset shows the signal-tone modulating signal. (b) Spectrum of the modulated pulse, which has a shape that is a scaled version of the temporal waveform. The dashed line shows the spectral response of the 60-channel bandpass filter with a channel spacing of 25 GHz. (c) Sampled microwave signal (blue circle in online version), which is obtained by measuring the output powers of the channels of the optical channelizer and normalized against the pulse spectrum shape, matches well with the original single-tone modulating signal (red dashed line in online version). (d) Fourier analysis of the sampled microwave signal after low-pass filtering.

under test is generated with the frequency-to-time mapping relation given by $\omega = t/\ddot{\Phi}$. The original single-tone microwave modulating signal is also plotted as a dashed line. It can be seen that the sampled signal obtained by spectrum filtering matches well with the modulating signal. The frequency of the measured signal is obtained by Fourier transform and low-pass filtering, with the result shown in Fig. 3(d). It clearly shows that the sampled signal has a single carrier frequency at 3.09 GHz. The measurement resolution is estimated to be $\sim$300 MHz, which is consistent with the temporal duration of the pulse ($\sim$3 ns). In this experiment, the frequency measurement error is about 30 MHz, which is resulted mainly from the limited number of sampling points and the measurement error of the dispersion value of the DCF.

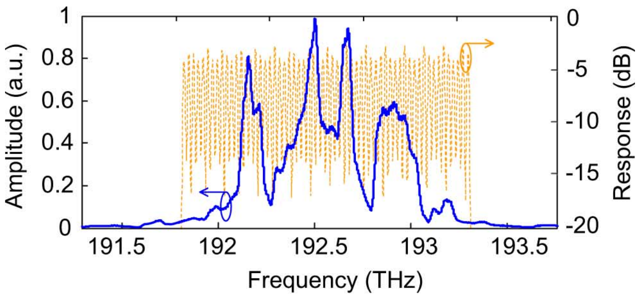
B. *Measurement of Multiple-Tone Microwave Signals*

One advantage of the proposed technique is that it has the capability of measuring a microwave signal with multiple frequencies. The frequency measurement of a microwave signal with multiple frequencies using the IMFI-TeCh is then experimented. As discussed, a conventional optical-channelizer-based technique can measure a microwave signal with multiple frequencies, but its measurement resolution is poor due to the relatively large channel spacing [15]–[19]. The proposed IMFI-TeCh can provide multiple frequency measurement with a much higher resolution. In the second experiment, a microwave signal with three tones at 0.92, 1.42, and 2.14 GHz, which is generated by an arbitrary waveform generator (Tektronix AWG7102), is employed as the signal under test and applied to the modulator. Fig. 4(a) shows the optical spectrum of the modulated optical pulse, which is then sampled by the 60-channel optical channelizer. The sampled spectrum, which is also normalized using the envelope of the Gaussian-shape pulse spectrum, is shown in Fig. 4(b). The equivalently sampled temporal waveform matches well with the original three-tone microwave signal, which is shown as a dashed line in Fig. 4(b). The Fourier transform of the sampled waveform after low-pass filtering is shown in Fig. 4(c). It is clearly seen that the sampled signal has three carrier frequencies at 0.95, 1.40, and 2.16 GHz, corresponding to the frequencies of three tones in the original microwave signal.

Note that, as shown in Fig. 4(c), the amplitudes of different sidebands do not represent the strengths of different frequencies from the actual microwave signal. By fully calibrating the frequency-dependent modulation efficiency, however, the amplitude of each frequency component of the microwave signal can be also obtained, making the system more practical.

C. *Measurement of a Frequency-Hopping Microwave Signal*

The proposed IMFI-TeCh technique can also be used to perform spectral analysis of a microwave signal with arbitrary spectrum. To evaluate this capability, a frequency-hopping microwave signal is tested. The frequency-hopping spread spectrum (FHSS) technique has been widely used in electronic warfare systems [34], where the carrier frequency of a transmitted microwave signal is rapidly switched (hopped) among many frequency channels in a pseudorandom sequence. Therefore, to effectively intercept and jam a frequency-hopping signal, the spectrum spreading characteristics (instantaneous frequency) has to be detected in real time. The proposed



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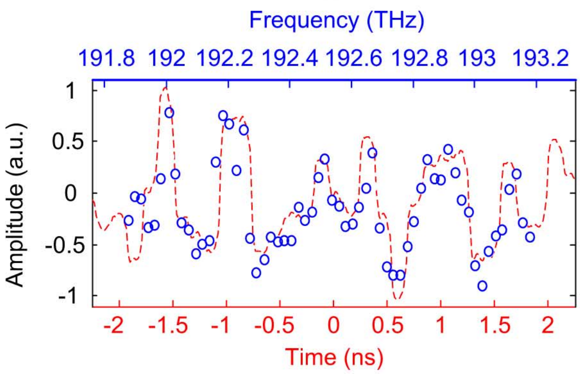

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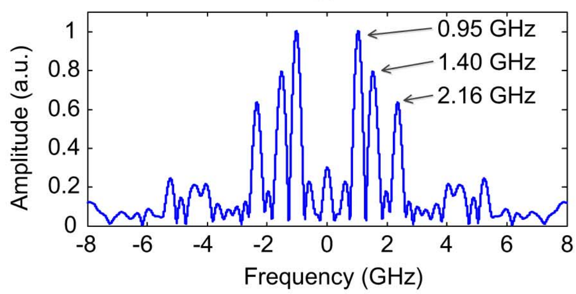
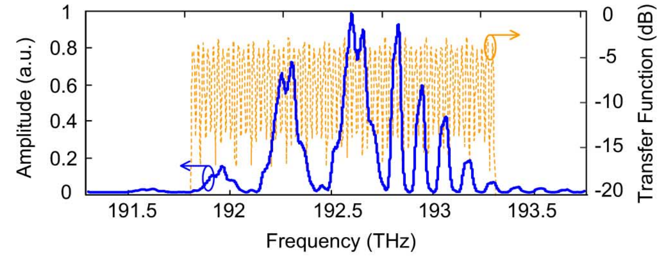


(c)

Fig. 4. Frequency measurement of a multiple-tone microwave signal. A three-tone microwave signal is generated by an arbitrary waveform generator and modulates the dispersed optical pulse. (a) Optical spectrum of the modulated optical pulse. The dashed line shows the spectral response of the optical channelizer. (b) Sampled signal (blue circle in online version), which matches well with the original modulating signal (red dashed line in online version). (c) Fourier transform of the sampled microwave signal after low-pass filtering, showing three carriers of 0.95, 1.40, and 2.16 GHz.

technique can fully reconstruct the temporal waveform at a high speed, thus enabling the spectral analysis of a frequency-hopping microwave signal. In the demonstration, we use the arbitrary waveform generator to generate a microwave signal with its carrier frequency switched between two frequencies of 1.02 and 3.06 GHz. The temporally stretched optical pulse is then modulated by this frequency-hopping microwave signal with its optical spectrum shown in Fig. 5(a). Fig. 5(b) shows the sampled version of the optical spectrum by the optical channelizer, which matches well with the original frequency-hopping microwave signal. The frequency distribution and instantaneous frequency of the measured signal is obtained via a Fourier transform and Hilbert transform [35], respectively, with the results shown in Fig. 5(c). It can be seen that the carrier frequencies and the frequency switching time have been accurately obtained from the sampled signal.



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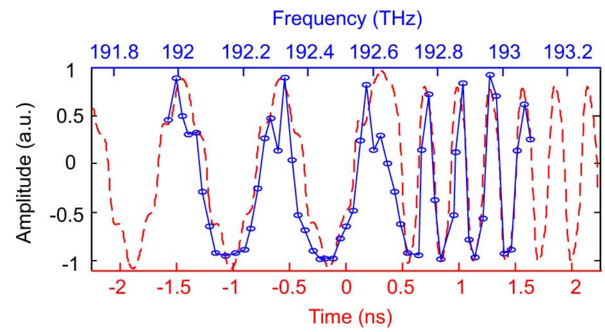

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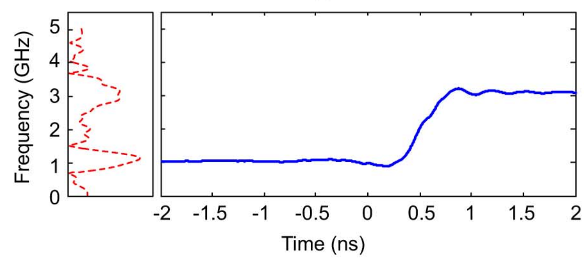

(c)

Fig. 5. Frequency measurement of a frequency-hopping microwave signal. (a) Optical spectrum of the modulated chirped pulse (solid line) and the spectral response of the optical channelizer (dashed line). (b) Sampled signal (blue circle in online version), which matches well with the original modulating signal (red dashed line in online version). (c) Instantaneous frequency of the sampled microwave signal obtained by Hilbert transform. (Dashed line: Fourier transform of the sampled signal.)

D. *Resolution Enhancement by Optical Spectrum Broadening*

The key advantage of the proposed technique is the significantly improved resolution compared with a conventional technique based on an optical channelizer with its resolution limited by the channel spacing. By equivalent temporal sampling using an optical channelizer, as described above, an improved resolution of $\sim$ 300 MHz has been achieved using an optical channelizer with a channel spacing of 25 GHz.

For practical applications, further improvement in frequency resolution is still required. According to (4), increasing the time duration of the temporally stretched optical pulse would lead to the improvement of the frequency resolution. By simply increasing the GVD, the stretched optical pulse can be further widened, but it may also reduce the equivalent sampling rate, as given by (3). Here, we propose to increase the time duration of the dispersed pulse via nonlinear optical spectrum broadening while maintaining the dispersion value, and hence, the sampling rate. As shown in Fig. 6(a), a transform-limited optical pulse generated from the mode-locked laser is first sent to an optical amplifier and a highly nonlinear fiber (HNLF) before

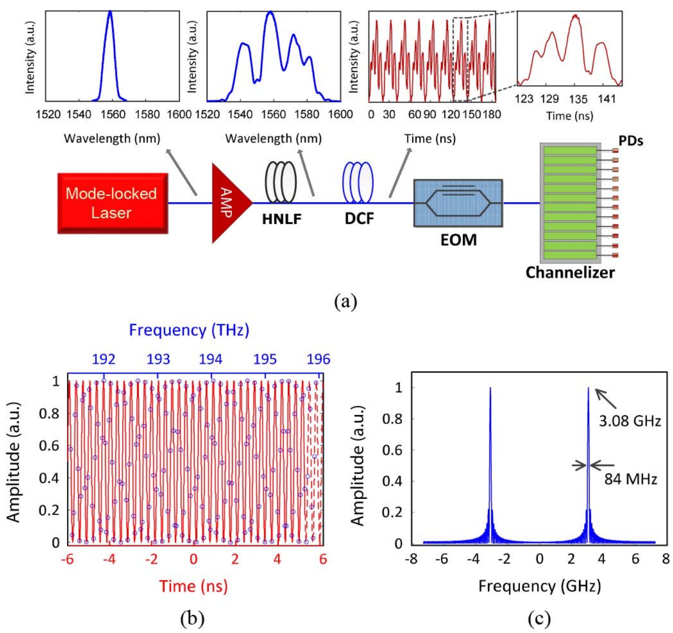

Fig. 6. Improvement of frequency measurement resolution by nonlinear optical spectrum broadening. (a) Scheme to improve the frequency measurement resolution by nonlinear optical spectrum broadening. The spectra of the original, spectrum-broadened, and temporally stretched optical pulses are all shown for comparison. (b) Powers at the outputs of the channels of the channelizer (blue circle in online versoin), which matches well with the single-tone microwave modulating signal (red dashed line in online version). (c) Fourier transform analysis showing the measured carrier frequency of 3.08 GHz and the effective frequency measurement resolution of 84 MHz. Amplifier: AMP; highly nonlinear fiber: HNLF; electrooptic modulator: EOM.

going through the dispersive Fourier transformation and modulation process. High-efficiency frequency conversion through self-phase modulation (SPM) and four-wave mixing (FWM) leads to substantial spectrum broadening. The FWHM bandwidth of the optical pulse is expanded from 8 to 43 nm. At the output of the DCF with the same GVD value, the optical pulse has been stretched to have a 10-dB time duration of 18 ns, as shown in Fig. 6(a), which corresponds to a duty cycle of 87%. The one-to-one mapping relationship still maintains between spectrum and time, confirming the dispersive Fourier transform of the spectrum-broadened optical pulse. Note that the broadened spectrum is not very flat, which may cause nonuniform signal-to-noise ratio within the broad spectral band. In fact, a flat and broad supercontinuum spectrum can be generated from an ultrashort optical pulse by engineering the dispersion profile of the nonlinear media [36], [37].

Measurement of a single-tone microwave frequency (3.06 GHz) is then experimentally demonstrated to evaluate the improvement of the frequency resolution. Fig. 6(b) shows the output powers from the channels of the optical channelizer with a channel spacing of 25 GHz, which is again normalized against the pulse spectrum envelope. Note that due to the limited operational bandwidth (from 1527.5 to 1567.5 nm) of the optical channelizer, the broadened optical spectrum is truncated and only two-thirds of the spectrum is used, which significantly degrades the effective frequency measurement resolution from the expected value. Fourier transform analysis of the sampled microwave signal is shown in Fig. 6(c). The carrier frequency of the microwave signal is measured to be 3.08 GHz with an effective frequency resolution of 84 MHz. In principle, if an optimized optical channelizer that can cover the full bandwidth of the broadened optical pulse is used, an expected frequency resolution of 55 MHz (1/18 ns) can be achieved, which is almost 500 times higher than the conventional techniques based on the direct use of an optical channelizer with a channel spacing of 25 GHz.

IV. Discussion

A. Design Considerations

We discuss the designer's equations, which predict the performance of the IMFI-TeCh system. Here, the key design parameters are the dispersion value, the repetition rate of the pulse train, and the channel spacing of the optical channelizer. Since these parameters are not independent, but interrelated, the values of the parameters thus need to be chosen carefully in order to optimize the performance of the system.

As stated above, the effective frequency measurement resolution (δf) is reversely proportional to the temporal width of the stretched pulse. Thus, an optical pulse with a longer temporal duration will result in a frequency measurement with a higher resolution. To avoid an overlap between two consecutive temporally stretched pulses, however, the temporal duration of the stretched pulse is limited by the repetition rate of the mode-locked laser source $(R_{\rm rep})$, which imposes the upper limit on the dispersion value given by $\Delta\omega_{\rm opt} \times \ddot{\Phi} < 1/R_{\rm rep}$. On the other hand, according to (3), smaller dispersion leads to a higher equivalent sampling rate, and hence, a larger frequency measurement range. To effectively capture a microwave signal with a carrier frequency at $\omega_{\rm RF}$, the temporal duration of the stretched pulse must be larger than the period of the microwave signal, which imposes the lower limit on the dispersion value given by $\Delta\omega_{\rm opt} \times \ddot{\Phi} > 2\pi/\omega_{\rm RF}$. Therefore, the dispersion value needs to be carefully selected based on the measurement requirements,

$$\frac{2\pi}{\Delta\omega_{\rm opt} \times \omega_{\rm RF}} < \ddot{\Phi} < \frac{1}{\Delta\omega_{\rm opt} \times R_{\rm rep}}. \tag{5}$$

Note that in the case of fully temporal stretching with a pulse duty cycle of 100% $(\Delta\omega_{\rm opt} \times \ddot{\Phi} = 1/R_{\rm rep})$, the maximum frequency measurement resolution is identical to the repetition rate of the pulse laser $\delta f_{\rm max} = R_{\rm rep}$. Therefore, a lower pulse repetition rate would offer a higher maximum frequency measurement resolution. However, a lower pulse repetition rate will reduce the update rate of the frequency measurement. Selection of the pulse repetition rate should be determined based on specific measurement requirements.

Moreover, according to (4), the frequency measurement resolution is independent of the channel spacing Ω. In fact, a smaller channel spacing will increase the equivalent temporal sampling rate for a given dispersion value. The maximum frequency that can be measured is determined by the equivalent sampling rate and the minimum frequency that can be detected is limited by the measurement resolution. Hence, the dynamic frequency measurement range is given by

$$D = \log_{10}\left(\frac{\omega_{\mathrm{RF\,max}}}{\omega_{\mathrm{RF\,min}}}\right) = \log_{10}\left(\frac{\Delta\omega_{\mathrm{opt}}}{2\times\Omega}\right). \quad (6)$$

Therefore, a smaller channel spacing and a wider optical spectral bandwidth would increase the number of samples, and hence, relax the tradeoff between the measurement resolution and measurement range for a given dispersion value.

B. Real-Time Measurement

An optical channelizer is a key device in the proposed IMFI-TeCh system. The powers at the outputs of the channels correspond to the sampled microwave signal. In the proof-of-concept experiments, a programmable optical spectral filter having a multiple-channel spectral response is functioning as the optical channelizer. An optical spectrum analyzer measures the filtered spectrum at the output of the channelizer. While the optical spectrum analyzer offers very good sensitivity, its update rate is very slow, usually only a few hertz. Therefore, real-time and single-shot measurement is not feasible, as the measured pulse spectrum has been averaged over millions of successive pulses. In addition, to obtain stable spectra of the modulated optical pulses for demonstration purposes, the frequency of the microwave signal has to be carefully selected as an integral multiple of the repetition rate of the pulsed laser source. In practice, however, if an actual optical channelizer, such as an optical demultiplexer, and a low-speed photodetector array are used [38], a microwave signal with arbitrary frequencies can be measured in real time with an update rate identical to the repetition rate of the pulse laser.

C. Frequency Measurement Range

In the proof-of-concept experiments, an optical channelizer with a channel spacing of 25 GHz is used. According to (3), the demonstrated system has an equivalent sampling rate of 14.8 GHz. Therefore, a microwave signal with a bandwidth up to 7.4 GHz can be measured according to the Shannon-Nyquist sampling theorem. An optical channelizer with smaller channel spacing would enable the measurement of a much higher frequency. For example, if a diffraction-grating-based optical channelizer with a channel spacing of 1 GHz is used [17], a frequency measurement range as high as 185 GHz can be achieved. It is also worth noting that if the incoming microwave signal is sparse in the frequency domain (for example, having only several discrete frequencies), a sub-Nyquist sampling rate is enough to recover the original signal based on compressive sampling [39]–[42]. Therefore, the proposed method can measure a spectrally sparse microwave signal with a much higher bandwidth with the help of the compressive sampling technique.

V. Conclusion

We have demonstrated a novel technique to perform IMFI with a high measurement resolution based on temporal channelization. This has been achieved by mapping the temporal waveform to the spectrum of a dispersed optical pulse based on dispersive Fourier transformation and then sampling the spectrum by an optical channelizer. The microwave signal was reconstructed from the sampled spectrum, and the spectral distribution of the signal was obtained by Fourier transform analysis. The proposed technique was experimentally evaluated. The spectral distributions of a single-tone, a multiple-tone, and a frequency-hopping microwave signal were accurately measured with a resolution of 300 MHz, using an optical channelizer with a channel spacing of 25 GHz. In addition, further improved measurement resolution as high as 55 MHz was achieved by nonlinear spectrum broadening, which is ~500 times higher than the channel spacing of the optical channelizer. The proposed technique provides a simple and effective solution for the real-time frequency measurement of microwave signals with sophisticated frequency distributions in wireless communications, radar, and electronic warfare systems.

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