Multiband microwave waveforms transmitting system using dual fiber combs

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ABSTRACT

In this work, a multiband microwave waveforms transmitting system was demonstrated based on all-optical dual fiber combs. Two optical fiber frequency combs via cascaded four waves mixing process ensure the coherence of the system by sharing the pump light. The high-speed frequency tuning of the pump laser will be transferred to each newly generated comb line through the nonlinear effect in the fiber. The comb pairs of the same order obtained through filtering transform the frequency chirp in the optical domain to the frequency chirp in the electrical domain after being beat on the PD. By changing the parameters of the control signal, the center frequency, bandwidth, PRF and envelope of the multi band microwave signal can be flexibly reconfigurable. Thanks to the coherence of dual optical frequency combs, microwave signals all show excellent line-type, high signal to noise ratio and no burrs. As a result, the chirped microwave signals of triangle wave, sine wave and sawtooth wave types are obtained at the repetition rate of 500 Hz. Overall, multi-band chirped microwave generation system based on all-optical system provides a practical device for transmitting and receiving multi band radar.

Keywords: microwave photonics, dual optical frequency comb, four wave mixing process

1. INTRODUCTION

Multi-band microwave waveforms have attracted much interest in diversified applications including modern radar systems, laser ranging, three-dimensional stereo imaging, and intelligent driving[1-5]. Especially, the linear chirped microwave signals can significantly improve the special measurement range and detection accuracy of the radar because of its defined waveform[6]. Recently, many methods of optically generating chirped microwave signals have been reported, such as photoelectric oscillation method, multi-heterodyne method based on electro-optic dual combs, etc[7-8]. Usually, the chirped microwave signals generated by all-optical method can reduce or even be unsuitable for electro-optical modulation devices, which is conducive to the portability and miniaturization of the system structure. However, these methods mentioned above more or less use electro-optical modulation devices, which makes the system actually an optoelectronic hybrid system rather than all-optical[9]. In 2020, Zhang *eal* demonstrated a linearly chirped microwave waveform (LCMW) photonic generation scheme, which applying a stimulated Brillouin scattering-based Fourier domain mode locked optoelectronic oscillator[6]. Although the parameters (the bandwidth, central frequency, duty cycle and repetition rate) of the linear chirped microwave signal can be flexibly tuned, the use of multiple electro-optical modulators and RF microwave sources in the system greatly increases the complexity of the system. Furthermore, such a system is vulnerable to electromagnetic interference, which further limits its application scenarios[10]. At present, however, chirped microwave signals generation based on all-optical system is rarely reported[11]. In addition, dual optical frequency combs source based on all-optical system is a potential light source for the generation of multi-band microwave waveforms[12]. Therefore, in this work, we demonstrated the generation multi-band microwave waveforms based on dual fiber combs. Two optical frequency combs based on cascaded four waves mixing process ensure the coherence of the system by sharing the same pump light. we typically transmit chirped microwave signals with triangular, sinusoidal and sawtooth envelopes, which all have clear line-type, high signal-to-noise ratio, and acceptable linearity. The bandwidth of the three chirped microwave signals is close to 1 GHz, and the time-varying voltage needs to be increased for further improvement. By setting the control signal, the generated microwave signals could be easily reconstructed, which has the same performance as the optoelectronic hybrid system.

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2. EXPERIMENT SETUP

The schematic diagram of the experimental system setup is showed in Fig.1. Two optical combs have the same device, including distributed feedback single frequency fiber laser (DFB-FL), erbium-ytterbium co-doped fiber amplifier (EYDFA), the bandpass filter, the optical circulator, the dispersion flattened highly nonlinear optical fiber (HNLF). The output spectrum was monitored by the optical spectrum analyzer (OSA, Advantest Q8384). Subsequently, after mixing, two optical combs were connected to programmable filter for filtering. Finally, it is captured by electronic spectrometer and high-speed oscilloscope via photoelectric detector.

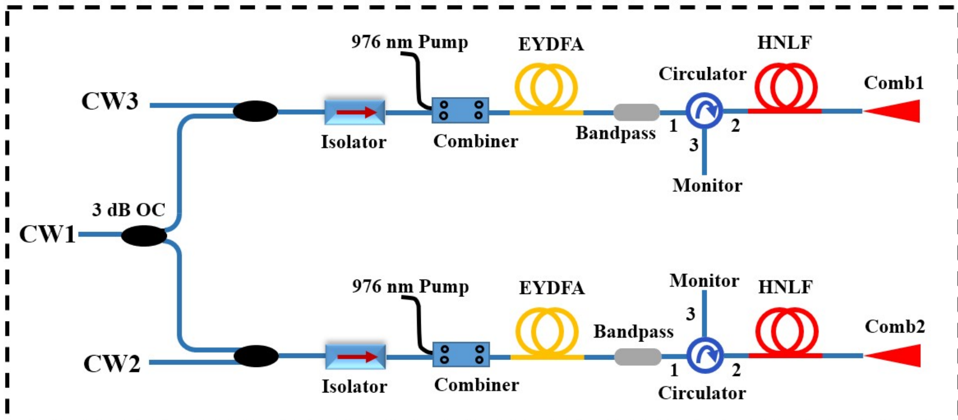

Figure 1. The Experimental Setup of the dual-fiber combs System.

Three continuous wave (CW) fiber lasers were used as the pump light for generating comb, where their output wavelengths could be tuned through the built-in temperature control module and PZT module. The wavelength tuning range of all used pump lasers could reach 0.8 nm, and the CW2 can obtained a fast frequency modulation range of 3GHz when its built-in PZT was loaded time-varying voltage. It is worth mentioning that the pumped lasers have excellent time-frequency characteristics in our experiments. For instance, the CW2's phase noise value is from -10 dBc/Hz to -148 dBc/Hz in the whole Fourier frequency range from 10 Hz to 1MHz (this value corresponds to the intrinsic linewidth with about 100 Hz) in our experiment. The relative intensity noise of the measured laser is, and the peak value is caused by the inherent relaxation oscillation in the fiber laser. It was followed by a home-made EYDFA to scale up the laser power, which was also necessary for obtaining high parametric gain. An isolator (ISO) was always used to block the backward-propagation light so as to protect the pump laser. The (2+1) ×1 pump combiner was used to deliver pump light to the gain fiber from a fiber-pigtailed multimode diodes with a total pump power of 25 W at 976 nm. The erbium-ytterbium co-doped single mode double-clad fiber (Nuffern:SM-EYDF-10P/125-XP) in EYDFA was used as gain fiber with core/cladding diameters of 10/125 μm and cladding absorption of 5 dB @976nm. A bandpass filter was fused behind the fiber amplifier to filter the spontaneous emission light in the spectrum. The amplified dual CW laser was injected into the highly nonlinear fiber through the port 1 of the circulator to complete the parameter conversion. The 3 ports of the optical circulator serve as monitoring, which is used to observe the Brillouin laser in reverse transmission in HNLF. By reducing the discharge power and extending discharge time stemmed from standard single-mode fusion splicer procedure, a thermal splicing approach was employed to connect the SMF-28e and the HNLF with a fusion-spliced loss of 0.5 dB. The length of the HNLF used in our experiment was 400m, which nonlinear coefficient is 10 $W^{-1}km^{-1}$ and the dispersion value is 0.389 ps/nm/km@1550nm. The squeezed polarization controller was placed between the HNLF and the 2 ports of the circulator, which was used to improve the degree of polarization of the dual pump light. Since all elements were directly spliced, this all-fiber microwave generation system was compact and flexible transmission.

Then, two optical frequency combs were injected into the multi-port programmable filter after being combined by 3dB OC. The comb line pairs of the same order obtained through filtering were beaten on PD respectively, where the optical signals were converted into electrical signals. The weak electrical signals were directly connected to the high-speed oscilloscope and electronic spectrometer through the low-noise RF power amplifier. The recovered instantaneous frequency is obtained from the data collected by high-speed oscilloscope through short-time Fourier transform. Strikingly, by changing the parameters of the control signal, the beat signals could be easily reconstructed.

3. RESULTS

In the experiment, the output power of DFB-FL1 were divided into two equal beams through 3dB OC, which were combined with two external single frequency lasers respectively and injected into the next stage to generate new comb lines through four wave mixing process. The DFB-FL1 not only acted as the pump light, but also as the reference frequency of the two optical combs. Therefore, its frequency stability would directly affect the signal-to-noise ratio and phase noise of the beat signal. It is worth noting that the four waves mixing process is phase sensitive, that is, the pump frequency line and the newly generated comb line are phase locked. The better the monochromaticity of the pump light, the lower the phase noise of the newly generated comb line. First, the wavelength interval between two pump lasers of one optical comb is set to 0.4 nm (separated by 50 GHz) and tuned by the temperature control module. The coupled dual initial pump light was amplified to 600mW, and then injected into the HNLF through the port 1 of the circulator. The output characteristics of the optical frequency comb based on the cascaded four wave mixing process, as shown in Fig. 2. Fig. 2(a) depicts the output optical spectral with the pump power of 500 mW. The comb spectrum had a central wavelength of 1550 nm and a spectral bandwidth of 4 nm (including 6 comb lines). As the pump power continues to increase, the number of comb lines will continue to increase. The newly generated comb lines were symmetrically and equally spaced on both sides of the double pump frequency, and the repetition frequency of the optical combs was always consistent with the frequency interval of the double pumping. Obviously, the generation of optical frequency combs based on traveling-wave four wave mixing process is the only scheme that can realize continuous tuning from GHz to THz at this stage. The adhesion at the bottom of the comb may be caused by nonlinear gain noise caused by modulation instability (MI). The linewidth of the first order comb line is shown in Figure 2 (b). The time-frequency characteristics of the dual-CW pump light would be directly mapped to the Stokes wave and anti-Stokes wave of each order. The pump laser had narrow linewidth characteristics, which could not only improve the parametric amplification efficiency, but also ensured that the parametric comb teeth have ultra-narrow linewidth as the pump light that triggers the four waves mixing process. The full width at half maximum (FWHM) of beat signal measured by delayed self-heterodyne method is 18.46 kHz, which corresponds to a real linewidth is less than 10 kHz. The inherent 1/f noise of a single frequency fiber laser made the beat signal line-type appear as a Gaussian function[13]. The red curve is the envelope of Gaussian function fitting. It is worth noting that the narrow linewidth of the comb line means that it has good monochromaticity and coherence, which is suitable for microwave emission.

In addition, the output wavelength of the single frequency fiber laser used in the experiment could be quickly tuned through the built-in PZT module. The maximum loadable voltage of PZT module is 150V in our experiment. We had typically tested the output frequency agility when the load voltage was 30V. The frequency variation and output power stability, as shown in Fig.3. The purple spherical dot chart shows that the frequency agility range is 3.7GHz, and performs a good linear frequency modulation trend. The pink curve indicates the stability of the output power during the frequency modulation of the pump laser.

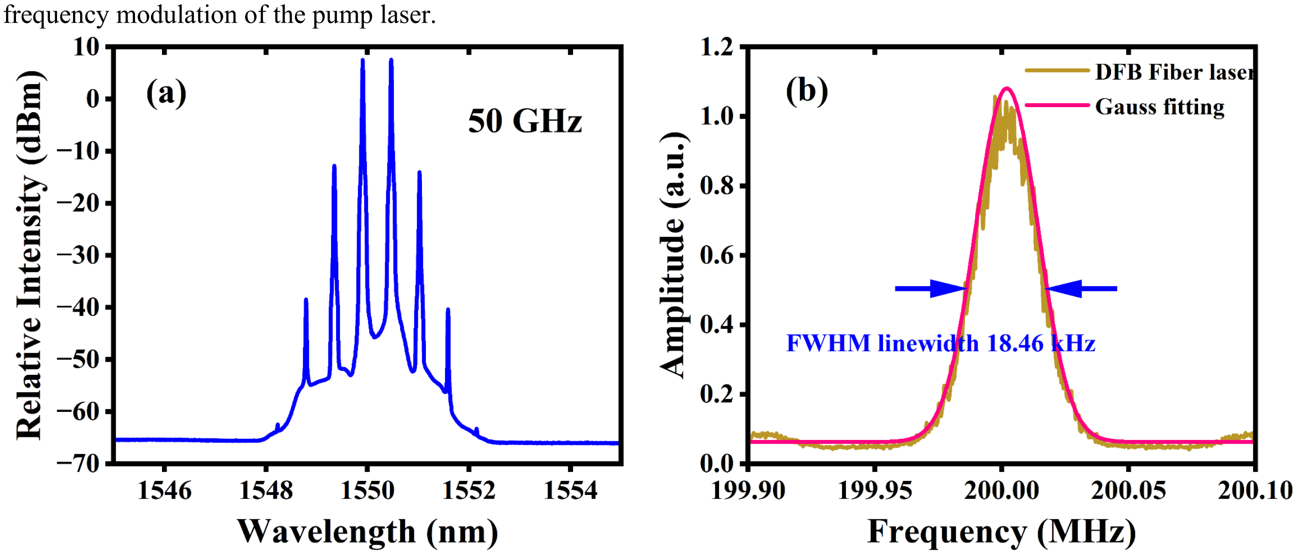

Figure 2. (a) Optical spectrum of optical frequency combs

by OSA at 0.02 nm RBW. (b) The delayed self-heterodyne beating radio frequency spectra of first order comb lines.

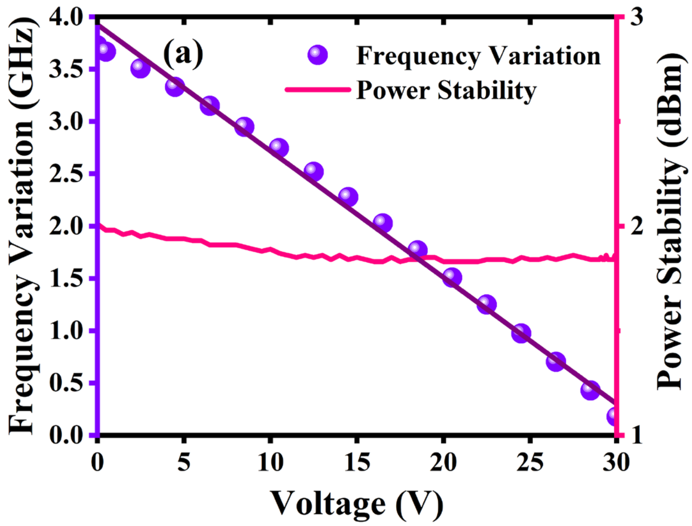

Figure 3. The measured frequency sweeping range of our laser under different driving voltage (Vpp) and power stability.

The principle of microwave generation based on dual frequency comb depends on the coherent transmission of broadband optical field to equivalent electrical domain signal. In order to take advantage of the aforementioned dual-fiber comb system, we demonstrated multi-band microwave signals transmission. As shown in Fig. 4(a1) -(c1), we representatively summarize the output waveforms of the beat signals with envelope of trigonometric wave, sine wave and sawtooth wave, respectively. The correspondingly instantaneous frequency by short-time Fourier transform, shown in Fig. 4(a2)–(c2). Consequently, the parameters of the dual-fiber combs source, such as coherence, modulation bandwidth, comb flatness and number of lines, are very important to the signal to noise ratio and frequency band of microwave signals.

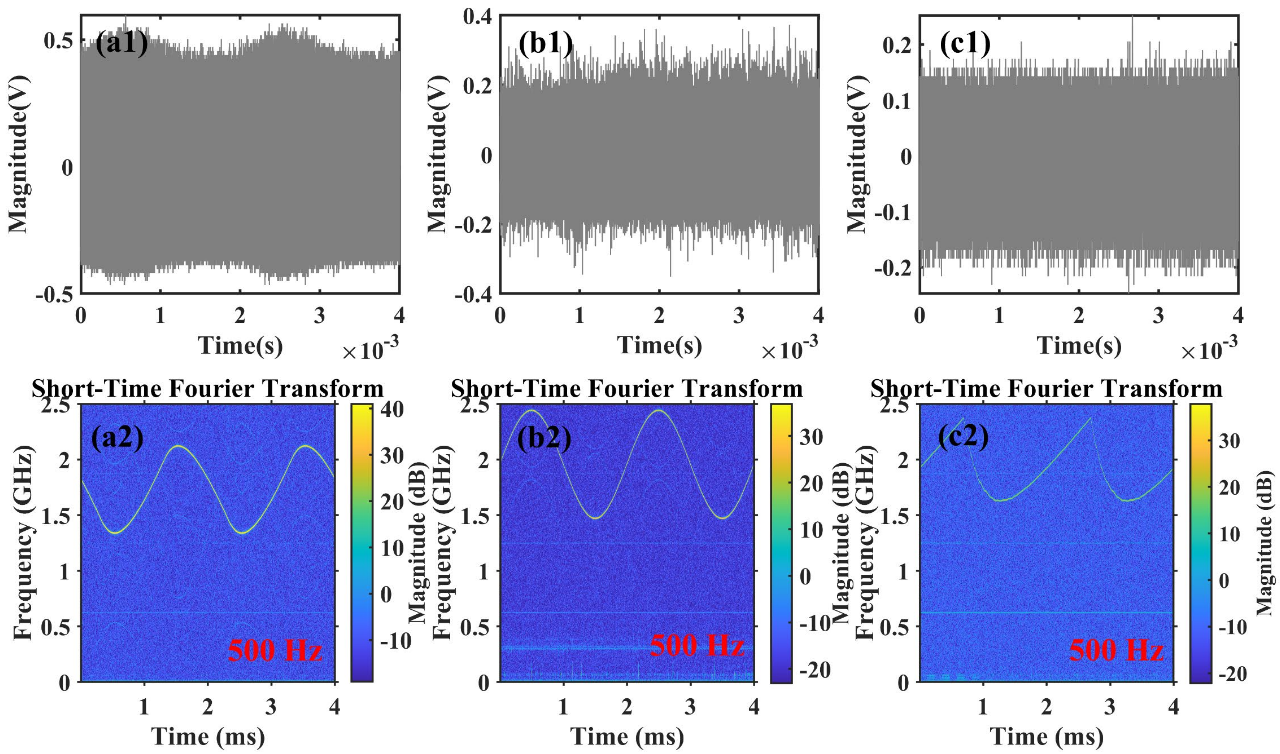

Figure 4. (a1), (b1), (c1) waveform; (a2), (b2), (c2) the recovered instantaneous frequencies corresponding to the(a1), (b1) and (c1).

4. CONCLUSION

In conclusion, a multiband microwave waveforms transmitting system using dual fiber combs was demonstrated. The generated microwave waveforms had three envelopes (trigonometric wave, sine wave and sawtooth wave) at repetition rate of 500 Hz. The high signal-to-noise ratio of the microwave signals once again verify the high coherence of the dual optical combs system. The parameters of microwave signals could be flexibly tuned by external control signal. In the future, efforts will be made to further increase the number of comb lines and the flatness of the comb lines to achieve stable transmission of more wavebands.

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