CW frequency comb generated by four-wave mixing and cascaded FWM

Guo Shuhuai[1], Wang Tianhe[2], Guo Huang[3], Qiao Bin[1*], Wang Xiao[1]

(1. Xingtai Medial College, Xingtai 054000, China;
2. Tianjin Jinhang Research Institute of Technical Physics, Tianjin 300308, China;
3. Xingtai Medical Third Affiliated Hospital, Xingtai 054000, China)

Abstract: In order to solve the problem of generating optical frequency comb by mode-locked laser seed source, a new method to generate optical frequency comb by continuous light source was presented and the problem of phase mismatch in four-wave mixing and cascaded four-wave mixing with wide spectral range was solved by using dispersion-flattened highly nonlinear optical fiber. We experimentally demonstrated efficient generation of an equalized optical comb with nearly 40 nm bandwidth. The comb was generated by low-power, low-cost, continuous-wave seeds(FP-LDs) without needing for pulsed laser sources. The CW frequency comb were generated by four-wave mixing (FWM) and cascaded FWM whose bandwidth of the spectrum was expanded by nearly 10 times and the linewidth of the frequency comb was 4.3 MHz with 420 m zero-slope dispersion dispersion-flattened HNLF.

Key words: four-wave mixing;　CW frequency comb;　linewidth of MHz;　zero-slope dispersion dispersion-flattened HNLF

CLC number: TN248　　**Document code:** A　　**DOI**: 10.3788/IRLA201847.0706007

四波混频和级联四波混频效应产生的连续光频率梳

郭树怀[1],王天鹤[2],郭　煌[3],乔　斌[1*],王　晓[1]

(1. 邢台医学高等专科学校,河北 邢台 054000; 2. 天津津航技术物理研究所,天津 300308;
3. 邢台医专第三附属医院,河北 邢台 054000)

摘　要: 针对产生光频率梳需要锁模激光种子源的难题,创新性提出了用连续光源产生光频率梳,应用色散平坦高非线性光纤解决了宽光谱范围四波混频和级联四波混频效应的相位失配问题。通过实验展示了近 40 nm 带宽的光频率梳的形成,光频率梳由低功耗,低成本,连续波种子(法布里-珀罗激光器)生成,无需脉冲激光源。连续光频率梳是由在 420 m 零色散色散平坦高非线性光纤中的四波混频和级联四波混频效应产生的,频谱带宽扩展了近 10 倍,频率梳的线宽为 4.3 MHz。

关键词: 四波混频;　连续光频率梳;　线宽 MHz;　色散平坦高非线性光纤

收稿日期:2018-02-05;　修订日期:2018-03-03

作者简介:郭树怀(1965-),男,副教授,主要从事影像电子学基础、电子电工、医学物理学等方面的研究。Email: guo-shuhuai@163.com
通讯作者:乔斌(1981-),男,讲师,主要从事电子信息、计算机教学和网络应用研究。Email: xtqiaobin@163.com

0 Introduction

The femtosecond laser-based frequency comb has played a key role in high-precision optical frequency metrology for a decade. A wideband generation of frequency combs has been demonstrated in both crystalline and fiber devices[1-11]. Although often referred to as a precise optical frequency ruler, its tick marks are in fact too densely spaced for direct observation and individual use, limiting important applications in remote sensing[5], spectroscopy[8], clock distribution[9], ranging [10], astronomy, photonics to RF frequency mapping [11] and ultrafast electromagnetic waveform control [12]. Additionally, in the remote sensing and remote transmission, the pulse-width of the femtosecond laser-based frequency comb is broadening because of the dispersion when it propagates in the fiber; the spectral width of the frequency comb is reduced.

To our knowledge, there is no report about the CW frequency comb. In this paper, a novel and simple method to generate the CW frequency comb is proposed and demonstrated which the tick marks are 40 GHz. Evgeny Myslivets used a beat tone as a seed source which is generated by two CW lights previously. The beat tone is a pulsed light. So we use only one CW light instead of the pulsed beat tone as the seed source to produce the CW frequency comb. Well, the CW light used here needs special requirements. This technique relies on four-photon mixing (FPM), so there are at least two discrete spectrum peak in the spectrum of the CW light which can generate four wave mixing (FWM) and cascade FWM effects to form the new frequency side mode, and new spectrum component. During the FWM and cascade FWM process, the CW seed source will not make any change in the time domain, only the spectrum of the seed source will be broaden because of the new frequency side mode and the new spectrum component which generated by the mixing process.

1 Experiment step

The generation of the CW frequency comb is shown in Fig.1. FP laser diode is the seed source in this experiment which the free spectrum range(FSR) is 0.3 nm(37.5 GHz frequency interval at about 1 550 nm). The driving current is 300 mA. According to the previous discussion, the power of the pump light is high enough to get a wide bandwidth spectrum of the CW comb frequency. So the FP-LD is amplified to 1 W by the erbium-doped fiber amplifier(EDFA). The model of the EDFA is EAR -2K -C and its manufacturer is IPG. The amplified FP light incidences into the HNLF and stimulates the FWM effect, generating the new sidebands and spectrum components. As the waves propagate through the fiber, FWM processes may occur involving the waves generated previously, creating in this way photons at further new frequencies. This is referred to as cascaded or multiple FWM. This frequency cascading is formed by signals with well defined frequency and phase differences. Also the cascaded FWM generated more new sidebands and more spectrum components. After the effects of the FWM and cascaded FWM, the output light is a CW, wide bandwidth spectrum frequency comb. It can be seen in the connected optical spectrum analyzer (OSA). The model of OSA is Anritsu MS9740A and the highest resolution is 0.03 nm.

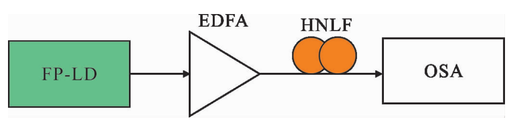


Fig.1 Experiment diagram of generation frequency comb

In order to compare the influences of phase mismatch to the efficiency of producing the FWM and cascaded FWM, we used two different types of the HNLF in the experiment, one is a standard HNLF, the other is zero-slope dispersion dispersion-flattened HNLF. The amplified FP light propagates through the two different types of the HNLF respectively and the different results of the frequency comb were compared. The length of the two types HNLF is the same, 420 m, and the nonlinear factor is the same, 10.8(W·km^{-1}). The effective area of the two different types is the same too, 11.6 μm. The only difference is the slop of the dispersion, the dispersion slop of the standard HNLF is 0.019 (ps·nm^{-2}·km^{-1}) and the dispersion slop of the dispersion-flattened HNLF is 0.006 (ps·nm^{-2}·km^{-1}). Firstly we used the standard HNLF to generate the CW frequency comb.

2 Results and discussion

Figure 2 (a) shows the spectrum of the FP-LD which the 3 dB bandwidth is only 3.180 nm. After the FWM and cascaded FWM in the HNLF, the spectrum of the new CW frequency comb is shown in Fig.2(b). It can be seen that the 3 dB bandwidth is broadened to 7.709 nm which is nearly three times wider than the original spectrum bandwidth. Because of the FWM and cascaded FWM effects, the idler beam and new generated sidebands expand the spectrum. In order to compare the effects of the FWM and cascaded FWM on the spectrum of the FP-LD, the spectrum of FP-LD which before enters to the HNLF and the spectrum of CW frequency comb which is output from the HNLF are both shown in Fig.2(c).

From Fig.2 (c) it can be seen obviously that many sidebands and new frequency components are generated by FWM and cascaded FWM. The wavelength lines which cover the spectrum of 1 547-1 551.5 nm are the pure pump lights in the FWM and cascaded FWM effects. The power of these wavelength lines is reduced. The consumption energy is used to amplify signal lights and produce new idle lights in the FWM and cascaded FWM effects. The wavelength lines which cover the spectrum of 1 542.5-1 547 nm are the mixing of the pump lights and signal lights. Because the power of this band is nearly the same, not changed obviously after the FWM and cascaded FWM effects. The wavelength lines of 1 542.5-1 547 nm firstly act as signal lights and are amplified by the pure pump lights in the FWM and then act as pump lights in the cascaded FWM effects. The power of the amplified lights is declined to amplify the pure signal lights and generate the idler beam.

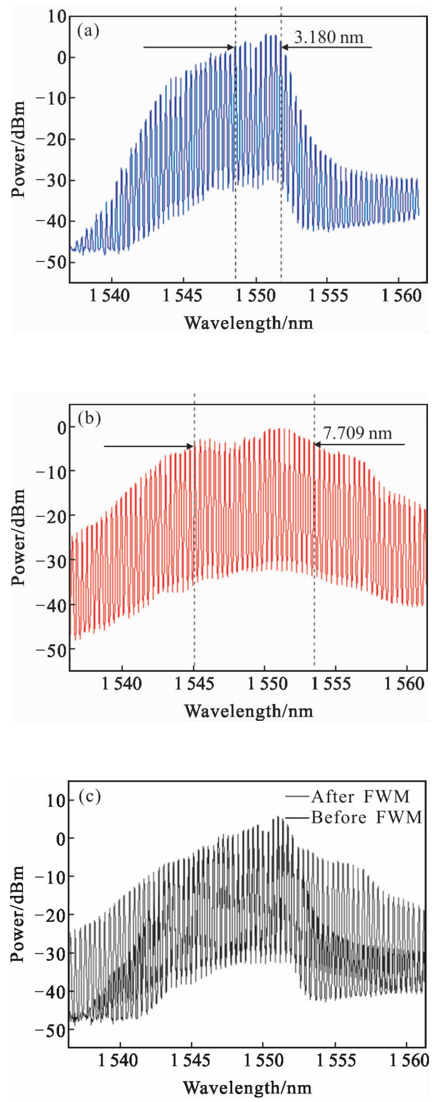


Fig.2 (a) Spectrum of FP-LD, (b) spectrum of the CW frequency comb after the standard HNLF, (c) spectrum of FP-LD which before enters to the standard HNLF and the spectrum of CW frequency comb which is output from the HNLF

The rest of the wavelength lines which cover the spectrum of 1 536.5-1 542.5 nm and 1 551.5-1 561.5 nm are the pure signal lights and idle lights. The new idle light beams and new frequency components which are generated by FWM and cascaded FWM effects are amplified by 20 dB compared with the same wavelength lines of the FP-LD.

In order to compare the linewidths of the FP-LD and the CW frequency comb (the new generated wavelength lines, the idler beam), we first measured the linewidths of the FP-LD. The wavelength lines are the longitudinal modes in the same cavity so the linewidths of the multi-wavelength are the same. So we only need to measure the linewidth of any one wavelength line to act as the linewidths of the FP-LD. In our experiments, a tunable filter is used to filter out a single wavelength line. The FSR of the FP-LD is 0.3 nm (37.5 GHz), therefore the bandwidth of the tunable filter is required to be less than 0.3 nm to filter out only one wavelength. The type of the tunable filter is OTF-350 which is manufactured by Santec Company and its minimum filter bandwidth is 0.1 nm.

From Fig.3 (a) it can be seen that the whole wavelength line is filtered out without any other wavelength line of the FP-LD. The signal-to-noise ratio (SNR) is as high as 60 dB. There are some spurs lines at the bottom of Fig.3 (a) which below -50 dBm. These spurs are the background noises and will not affect the linewidth measurement of the FP-LD. From Fig.3(b) it can be seen that the bottom noise of FP-LD is -47 dBm which is higher than -50 dBm, so the spurs are background noises.

For characterization of optical spectral linewidth, a standard delayed self-heterodyne method for single wavelength linewidth measurement is used; In our delayed self-heterodyne measurement system, a length of 4 km SMF and a microwave spectrum analyzer (MSA, Agilent Technologies N9010A) are used to measure the radio frequency (RF) spectra of the CW light for characterization of the optical spectral linewidths. Fig.3 (c) is the RF spectra of the single beat signals which is picked up by the tunable filter from the FP-LD. The linewidth of the wavelength line is 4.3 MHz which means the linewidth of the FP-LD is 4.3 MHz too.

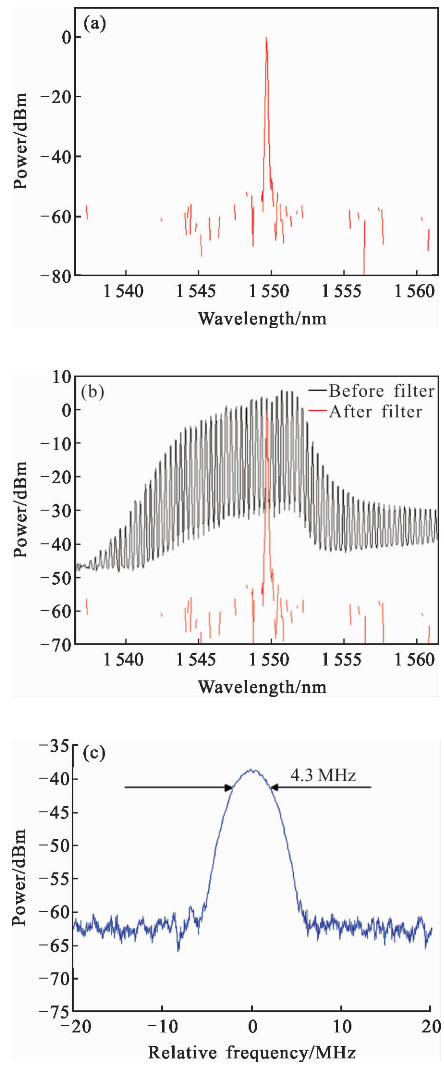
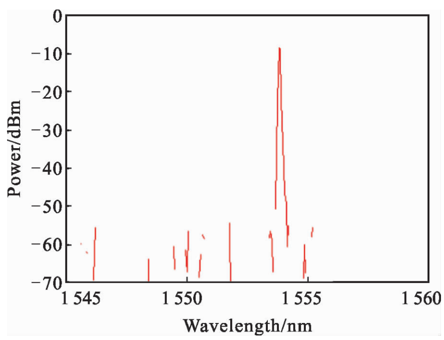


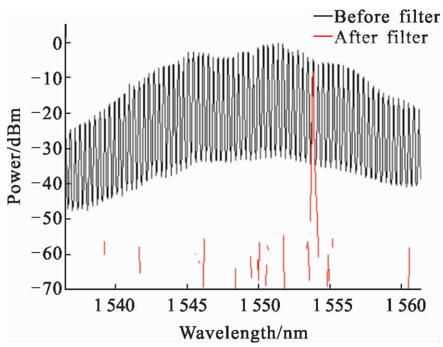
Fig.3 (a) Spectrum of the single wavelength which after the tunable filter, (b) spectrum of the single wavelength which after the tunable filter and the spectrum of the FP-LD, (c) RF spectra of the single beat signals which is picked up by the tunable filter from the FP-LD

Then, we measured the linewidths of new generated CW frequency comb with 420 m standard HNLF. The linewidths of the originally spectrum component would not change after the FWM and cascaded FWM effects. So we just need to measure the linewidths of the new generated wavelength lines, idler beams. The wavelength lines which cover the spectrum of 1 551.5-1 561.5 nm are the pure signal lights and idle lights. The center wavelength of the tunable filter was set at 1 553.85 nm in the experiment.

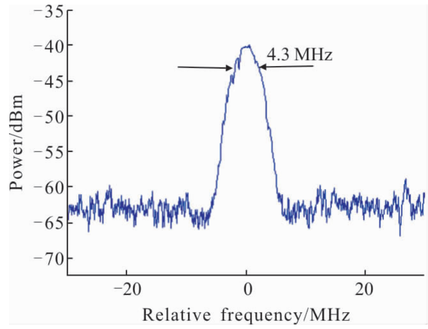
From Fig.4 (a) it can be seen that the SNR of the filtered out wavelength line is 50 dB. The spurs at the bottom of Fig.4 (a) are also the spectrum of background noises whose power are below −50 dB. The spectrum of the CW frequency comb with the tunable filter (red curve) and without the tunable filter (black curve) are shown in Fig.4 (b). It can be seen that the power of the background noises is far smaller than the power of the bottom noises of the FP−LD. From Fig.4 (c) we can see that the linewidth of the filter out wavelength line is 4.3 MHz, so the linewidths of the new generated spectrum are 4.3 MHz. From Fig.4 (d) it can be seen that the power of the single wavelength line is higher than the power of the same wavelength of the FP−LD by 10 dB without the insert loss of the filter. The wavelength line is the new generated sideband and the linewidth of the new generated CW frequency comb is 4.3 MHz which is as the same as the linewidth of the FP−LD.



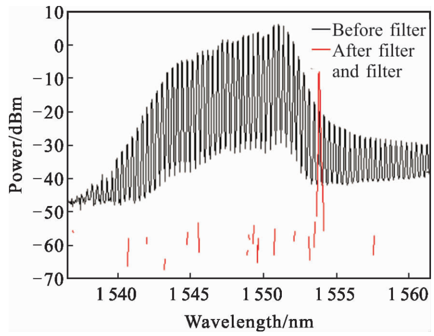
(a) Spectra of the single wavelength which is picked up by the tunable filter from CW frequency comb



(b) Spectrum of the CW frequency comb with the tunable filter (red curve) and without the tunable filter (black curve)



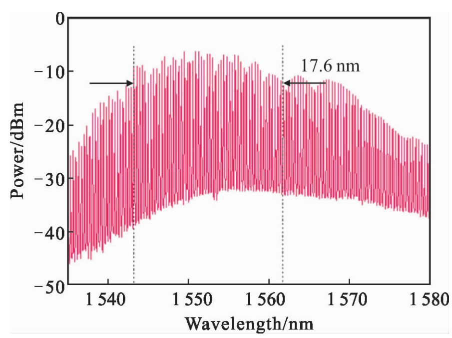
(c) RF spectra of the single beat signals which is picked up by the tunable filter from CW frequency comb



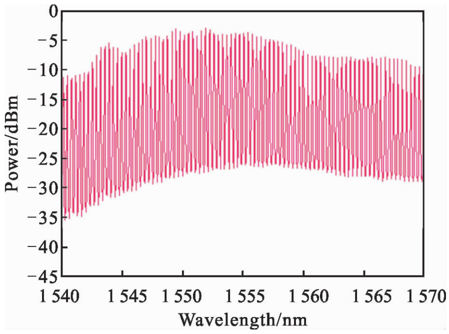
(d) Spectrum of the single wavelength with the tunable filter which is generated by FWM and cascaded FWM (red curve) and the FP−LD (black curve)

Fig.4 Spectrum of the CW frequency comb with 420 m standard HNLF

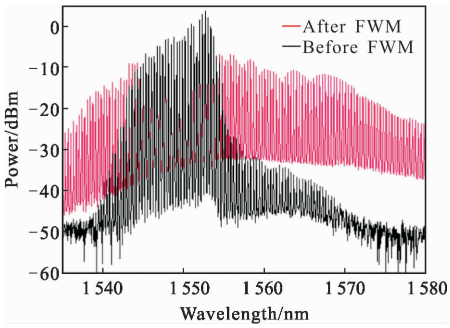
The zero-slope dispersion dispersion-flattened HNLF is connected to the amplified FP−LD which the length is all the 420 m in the next experiment. Fig.5 is the spectrum of the CW frequency comb with 420 m zero-slop dispersion HNLF. From Fig.5(a) it can be seen that the 3 dB bandwidth of the spectrum of the new generated CW frequency comb is 17.6 nm which is nearly 6 times more than the 3 dB bandwidth



(a) Spectra of the CW frequency comb which is output from 420 m zero-slop dispersion HNLF



(b) Zoomed-in view of (a) at 1 540–1 570 nm

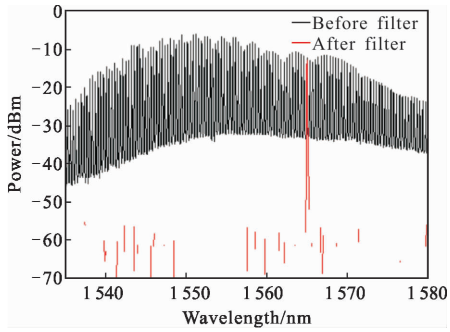


(c) Spectrum of the FP–LD (black curve) and the CW frequency comb (red curve)

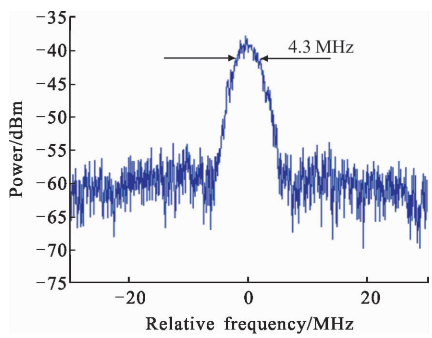
Fig.5 Spectrum of the CW frequency comb with 420 m zero-slop dispersion HNLF

of the FP–LD spectrum, and 3 times more than the 3 dB bandwidth of the CW frequency comb with 420 m standard HNLF.

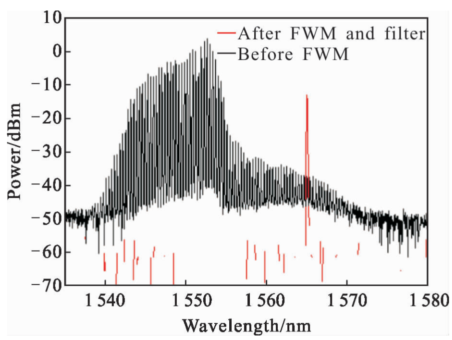
Also we measured the linewidths of new generated CW frequency comb with the zero-slope dispersion dispersion-flattened HNLF which the length is 420 m. As shown in Fig.5. The wavelength lines which cover the spectrum of 1 560–1 580 nm are the pure signal lights and idle lights. The center wavelength of the tunable filter was set at 1 565.15 nm in the experiment. It can be seen that the SNR of the filtered out wavelength line is 50 dB in Fig.6(a). From Fig.6(b) we can see that the linewidth of the filter out wavelength line is 4.3 MHz, so the linewidths of the new generated spectrum by the zero-slope dispersion dispersion-flattened HNLF are 4.3 MHz. In order to ensure the filter out wavelength is pure signal light or idle light, we compare the spectrum of the FP–LD and the spectra of the single wavelength line which are both shown in Fig.6(c). From Fig.6(c) it can be seen that the power of the single wavelength line is higher than the power of the same wavelength of the FP–LD by nearly 30 dB without the insert loss of the filter. The filter out wavelength line is the new generated sideband and the linewidth of the new generated CW frequency comb is 4.3 MHz which is as the same as the linewidth of the FP–LD as the same with the standard HNLF.



(a) Spectrum of the CW frequency comb with the tunable filter (red curve) and without the tunable filter (black curve)



(b) RF spectra of the single beat signals which is picked up by the tunable filter from CW frequency comb with 420 m zero-slop dispersion HNLF



(c) Spectrum of the single wavelength with the tunable filter which is generated by FWM and cascaded FWM (red curve) and the FP–LD (black curve)

Fig.6 Linewidth of the CW frequency comb with 420 m zero-slop dispersion HNLF

3 Conclusion

In this paper the method of the efficient generation of an equalized optical comb with nearly 40 -nm bandwidth is proposed. The comb was generated by CW FP-LD seeds without pulsed laser sources. We analyze the effect of the dispersion slope on the efficiency of the four-wave mixing and cascade four-wave mixing effect, and solve the phase mismatch of the four-wave mixing by using the dispersion-scattered zero-dispersion fiber to enhance its efficiency. The bandwidth spectrum of generated CW frequency comb are expanded by nearly 10 times with 420 m zero-slope dispersion dispersion-flattened HNLF. The four-wave mixing and cascading four-wave mixing effects do not widen the linewidth. The linewidth of new generated CW frequency comb is 4.3 MHz through experimental testing.

References:

[1] Bartels A, Heinecke D, Diddams S A. 10-GHz self-referenced optical frequency comb [J]. ***Science***, 2009, 326(5953): 681.

[2] Ding Xiangdong, He Wei, Yao Qifeng, et al. Switchable erbium-doped fiber laser utilizing tunable Mach-Zehnder filter [J]. ***Infrared and Laser Engineering***, 2017, 46(10): 1005006. (in Chinese)

[3] Kippenberg T J, Holzwarth R, Diddams S A. Microresonator-based optical frequency combs[J]. ***Science***, 2011, 332(6029): 555-559.

[4] Yu Meng, Zhang Yong, Jin Chenfei, et al. Improving the efficiency of microwave photonics scanning frequency measurement based on vernier effect [J]. ***Infrared and Laser Engineering***, 2016, 45(11): 1117004. (in Chinese)

[5] Schliesser A, Brehm M, Keilmann F, et al. Frequency-comb infrared spectrometer for rapid, remote chemical sensing [J]. ***Opt Express***, 2005, 13(22): 9029-9038.

[6] Cundiff S T, Ye J. Colloquium: Femtosecond optical frequency combs [J]. ***Rev Mod Phys***, 2003, 75(1): 325-342.

[7] Newbury N R, Swann W C. Low-noise fiber-laser frequency combs[J]. ***J Opt Soc Am B***, 2007, 24(8): 1756-1770.

[8] Holzwarth R, Udem T, Hänsch T W, et al. Optical frequency synthesizer for precision spectroscopy [J]. ***Phys Rev Lett***, 2000, 85(11): 2264-2267.

[9] Sprenger B, Zhang J, Lu Z H, et al. Atmospheric transfer of optical and radio frequency clock signals [J]. ***Opt Lett***, 2009, 34(7): 965-967.

[10] Balling P, Kren P, Mašika P, et al. Femtosecond frequency comb based distance measurement in air [J]. ***Opt Express***, 2009, 17(11): 9300-9313.

[11] Inaba H, Daimon Y, Hong F L, et al. Long-term measurement of optical frequencies using a simple, robust and lownoise fiber based frequency comb [J]. ***Opt Express***, 2006, 14(12): 5223-5231.

[12] Jiang Z, Huang C B, Leaird D E, et al. Optical arbitrary waveform processing of more than 100 spectral comb lines [J]. ***Nat Photonics***, 2007, 1(8): 463-467.