Generation of ultra-wide and flat optical frequency comb based on electro-absorption modulator and frequency modulator[*]

GAO Di (高迪), LI Pei-li (李培丽), SHAO Qian (邵茜), and CHEN Jing-yuan (陈静远)**
College of Optoelectronic Engineering, Nanjing University of Post & Telecommunications, Nanjing 210023, China

(Received 8 December 2015)

An ultra-wide and flat optical frequency comb (OFC) generation scheme using multiple continuous wave (CW) light sources based on electro-absorption modulator (EAM) and frequency modulator (FM) is proposed. In the scheme, each CW light source is broadened and modulated by the first EAM and FM, respectively. The second EAM is introduced to flatten the ultra-wide OFC lines. By setting the wavelength spacing of light sources equal to the bandwidth of sub-OFC, an ultra-wide OFC can be obtained. Principle analysis and simulation for the scheme are performed. The results show that in the case of a single light source, a tunable and flat OFC is obtained. With the increase of light sources, the bandwidth of the generated ultra-wide OFC expands rapidly. In the case of 28 light sources, a 22 GHz ultra-wide OFC with bandwidth of 16.52 THz can be generated.

Document code: A **Article ID:** 1673-1905(2016)02-0097-4
DOI 10.1007/s11801-016-5250-z

Optical frequency comb (OFC) has drawn great attention due to its widespread applications in some areas, such as ultra-high precision detection, chemical composition detection and long distance communication. At present, a variety of schemes have been reported to generate OFC. An ultra-wide OFC can be obtained by using optical feedback, high order nonlinear fiber (HNLF) and erbium-doped fiber (EDF) to enhance the optical nonlinear effects[1]. However, due to the difficult control of optical nonlinear effects, the flatness of the generated OFC is poor. In contrast, OFC generation schemes using external modulators driven by radio frequency (RF) signals without complicated parameter control are simpler[2-6]. Unfortunately, due to the use of RF signal generators, these systems are always costly and only a few spectral lines can be obtained. To reduce the cost, another OFC generation method using optoelectronic oscillator (OEO) ring instead of RF signal generators was proposed[7,8]. However, the system is complex and the generated OFC is not tunable. Besides, some schemes, which introduced optical loop to expand OFC bandwidth, were reported[9-11] and an ultra-wide OFC with bandwidth of 1 THz was generated indeed. Moreover, the amplified spontaneous emission (ASE) noises are accumulated continually, which seriously affect the flatness of the generated OFC.

In this paper, we report an ultra-wide, flat and tunable OFC generation scheme using multiple continuous wave (CW) light sources based on electro-absorption modulator (EAM) and frequency modulator (FM). In the case of a single light source, the generated OFC has a bandwidth of 525 GHz with flatness of 0.81 dB. And in the case of 28 light sources, an OFC with bandwidth of 16.52 THz and flatness less than 2 dB is obtained.

The schematic diagram of the ultra-wide and flat OFC generation is shown in Fig.1. In the case of a single light source, the CW light from the tunable laser diode (TLD1) is broadened and modulated by EAM1 and FM, respectively. Thus, the output optical field of FM can be expressed as[12]

$$E_{\mathrm{FM}}=E_0\mathrm{e}^{\mathrm{i}(\omega_{\mathrm{c}}t)}T_{\mathrm{EAM}}(t)\cdot T_{\mathrm{FM}}(t)=E_0\mathrm{e}^{\mathrm{i}(\omega_{\mathrm{c}}t)}\cdot\mathrm{e}^{-(V/V_{\mathrm{e}})^a}\cdot\mathrm{e}^{\mathrm{i}m_{\mathrm{f}}\cos\omega_{\mathrm{m}}t}\,,\quad(1)$$

where ω_c and E_0 are the angular frequency and electric field amplitude of TLD1, respectively. $T_{\mathrm{EAM}}(t)$ and $T_{\mathrm{FM}}(t)$ are the transmittances of EAM and FM, respectively. V is the applied voltage of EAM1. V_e and a are two constants related to EAM1. m_f is the modulation index of FM, and $\cos\omega_m t$ is the driving signal of FM.

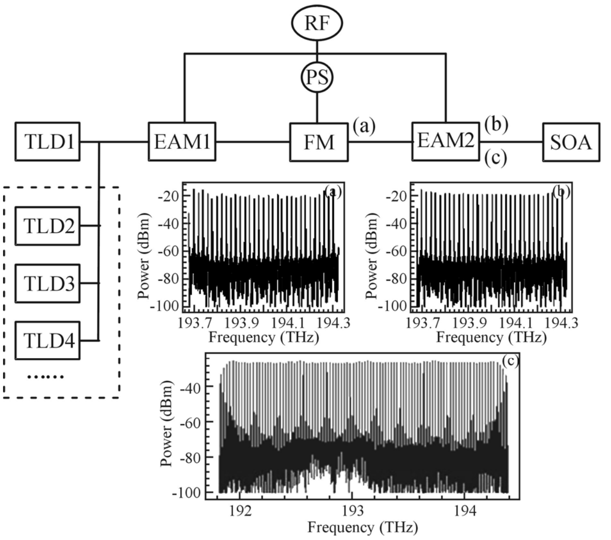
The corresponding spectrum at the output of FM is shown in Fig.1(a). EAM2 as a limiter reduces the power of the high spectral lines and increases the low ones. So the power difference in the spectrum is reduced and the flatness of the spectrum at the output of EAM2 can be further improved, as shown in Fig.1(b). EAM1, EAM2

---

[*] This work has been supported by the Specialized Research Fund for the National Natural Science Foundation of China (Nos.61275067 and 61302026), and the Provincial Natural Foundation of Jiangsu (Nos. BK2012830 and BK2012432).

** E-mail: lipl@njupt.edu.cn

and FM are driven by the same RF signal. Thus, the output optical field of EAM2 can be expressed as



TLD: tunable laser diode; EAM: electro-absorption modulator; FM: frequency modulator; RF: radio frequency; SOA: semiconductor optical amplifier

Fig.1 Schematic diagram of the ultra-wide and flat OFC generation and output spectra of (a) FM, (b) EAM2, and (c) the generated ultra-wide OFC

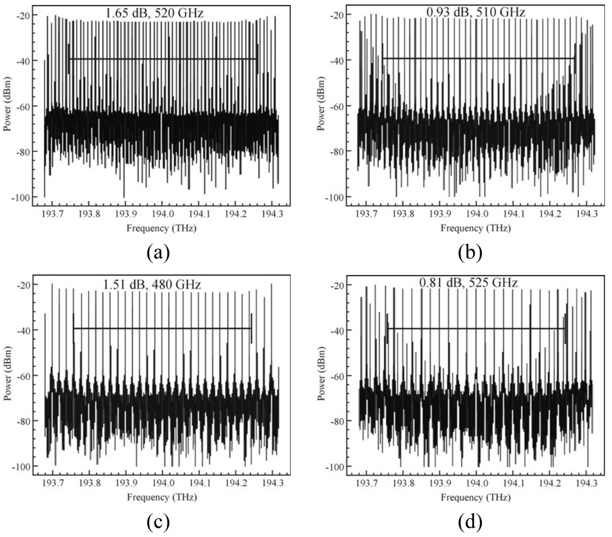
$$E_{\mathrm{EAM2}} = E_0 T_{\mathrm{EAM}}(t)^2 \cdot \sum_{-\infty}^{\infty} J_n(m_{\mathrm{f}}) \mathrm{e}^{\mathrm{i}(\omega_c t + n\omega_m t)} =$$
$$E_0 T_{\mathrm{EAM}}(t)^2 J_0(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t)} + E_0 T_{\mathrm{EAM}}(t)^2 J_1(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t + \omega_m t)} +$$
$$E_0 T_{\mathrm{EAM}}(t)^2 J_{-1}(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t - \omega_m t)} + E_0 T_{\mathrm{EAM}}(t)^2 J_2(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t + 2\cdot\omega_m t)} +$$
$$E_0 T_{\mathrm{EAM}}(t)^2 J_{-2}(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t - 2\cdot\omega_m t)} + E_0 T_{\mathrm{EAM}}(t)^2 J_3(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t + 3\cdot\omega_m t)} +$$
$$E_0 T_{\mathrm{EAM}}(t)^2 J_{-3}(m_{\mathrm{f}}) \cdot \mathrm{e}^{\mathrm{i}(\omega_c t - 3\cdot\omega_m t)} \ldots , \qquad (2)$$

where $J_n(\cdot)$ is the Bessel function with the order of n, where n=0, ±1, ±2, ±3.... The signal modulated by EAM is similar to Gaussian pulse, whose pulse shape is the spectral envelope. In the time domain, every term of Eq.(2) represents a Gaussian pulse, whose intensity varies with $\sin\omega_{\mathrm{m}}t$, and the frequency spacing is ω_{m}. In the frequency domain, each term represents a spectrum with the line spacing of ω_{m} and the frequency of $\omega_{\mathrm{c}}t+n\omega_{\mathrm{m}}$. Besides, the power of the nth spectrum varies with the value of $J_n(\cdot)$ and the power of spectral lines decays from the center line to side bands exponentially. Thus, the spectra are superimposed on each other, and the power of different frequencies increases by different values. However, the power of the center spectral line in the nth spectrum is the main power component at frequency of $\omega_{\mathrm{c}}t+n\omega_{\mathrm{m}}$. Due to the small difference between the increases at different frequencies, the power of spectral lines in the output spectrum is almost the same.

In the case of multiple CW light sources, light beams are coupled into EAMs and FM. Each light beam generates its sub-OFC. By setting the spacing between adjacent sub-OFCs exactly equal to the spectral line spacing, an ultra-wide OFC is obtained, as shown in Fig.1(c).

The parameters of the devices used in the system are as follows: the power of TLD is 1 mW with the linewidth of 10 MHz; two EAMs are both at reversed bias with the bias voltage of 1 V and the modulation voltage is 2 V; the frequency offset of FM is 600 GHz.

Only a single light beam with center frequency of 194 THz is launched to the optical path. Fig.2 shows the spectra of the obtained OFCs by setting the RF signal frequencies at 10 GHz, 15 GHz, 20 GHz and 25 GHz, respectively. From Fig.2, we can see that 4 OFCs with line spacings of 10 GHz, 15 GHz, 20 GHz and 25 GHz respectively are obtained. Due to the fixed bandwidth of output signal modulated by FM, the bandwidths of 4 OFCs are both 600 GHz determined by the frequency offset of FM. Besides, the flatness of boundary part in 4 OFCs becomes worse. Compared with the flatness of entire spectrum, that of the middle parts in 4 spectra is better. In order to get a good flatness, by intercepting bandwidths of 520 GHz, 510 GHz, 480 GHz and 525 GHz in 4 spectra, 4 OFCs with 52, 34, 24 and 21 lines and flatnesses of 1.65 dB, 0.93 dB, 1.51 dB and 0.81 dB are achieved. We can also see that the line number reduces with the increase of line spacing, and the power of spectra arises with the reduction of line number slightly.



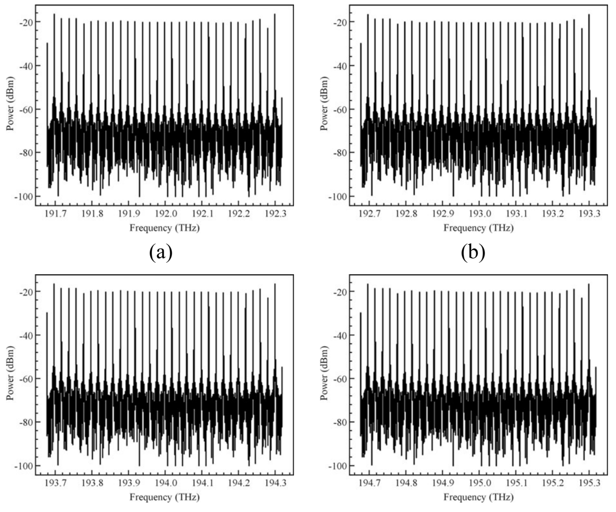
(a) (b)

(c) (d)

Fig.2 In the case of a single light source, the spectra of OFCs with different line spacings of (a) 10 GHz, (b) 15 GHz, (c) 20 GHz, and (d) 25 GHz

Fig.3 shows the spectra of generated OFCs with optical input frequencies of 192 THz, 193 THz, 194 THz and 195 THz, respectively, driven by a 25 GHz RF signal. The results show that the frequency of input light determines the center frequency of OFC. And with the increase of light frequency, the entire spectrum moves to high frequency region.

However, the spectral envelope is almost unchanged.

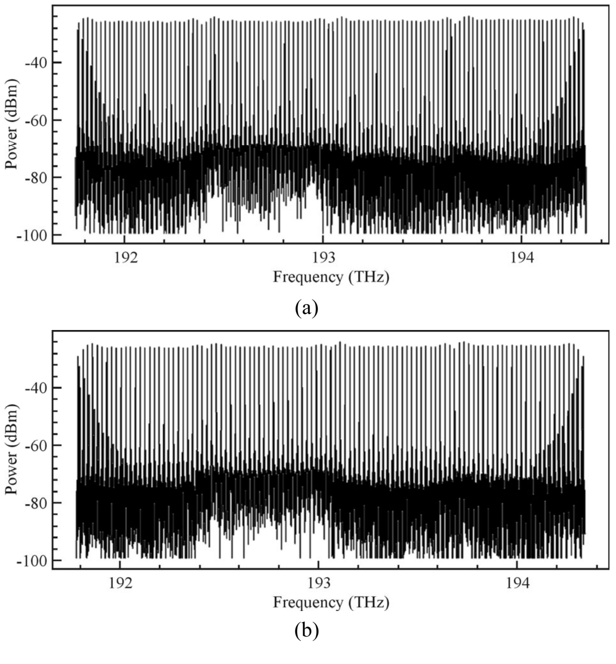


(a) (b)

(c) (d)

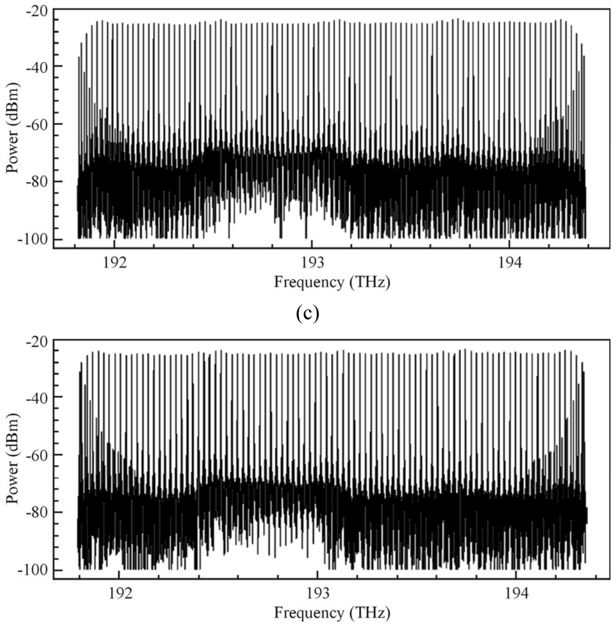
Fig.3 In the case of a single light source , the spectra of OFCs with different center frequencies of (a) 192 THz, (b) 193 THz, (c) 194 THz, and (d) 195 THz

In order to generate an ultra-wide OFC, multiple light sources are coupled into the light path. Fig.4 shows the spectra of generated OFCs with 4 different light sources. With RF signal frequencies of 22 GHz, 24 GHz, 26 GHz and 28 GHz, the wavelength spacings of light sources are equal to 638 GHz, 624 GHz, 598 GHz and 588 GHz, respectively. From Fig.4, we can see that the line spacings of generated OFCs are 22 GHz, 24 GHz, 26 GHz and 28 GHz, respectively. With the increase of line spacing, the line number decreases proportionally while the line power grows slightly. Also, the flatness is improved with the increase of line spacing. However, compared with the case of a single light source, the flatness of the ultra-wide OFC deteriorates slightly, due to the poor flatness of boundary part of sub-OFCs.



(a)

(b)

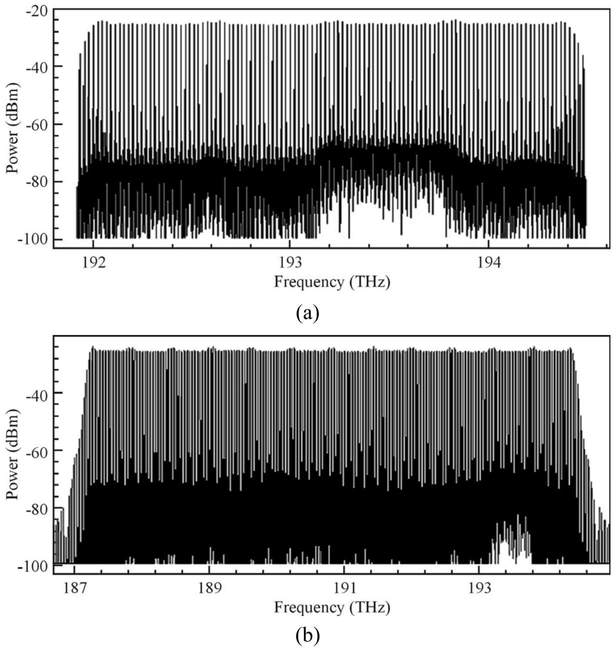


(c)

(d)

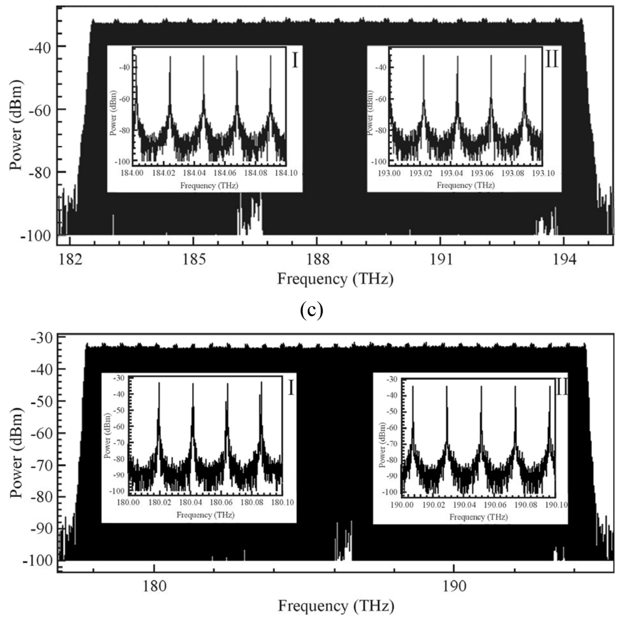
Fig.4 In the case of four light sources, the spectra of OFCs with different line spacings of (a) 22 GHz, (b) 24 GHz, (c) 26 GHz, and (d) 28 GHz

Fig.5 shows the spectra of generated OFCs with 4, 12, 20 and 28 light sources, respectively. Illustration I and II are the enlarged views of part of the spectra in Fig.5(c) and (d), respectively. From Fig.5, we can see that with the increase of light sources, the bandwidth of generated ultra-wide OFC expands rapidly and the flatness deteriorates slightly. Also, the average power decreases visibly. In Fig.5(d), when 28 light beams are coupled into the optical path, we can generate a 22 GHz ultra-wide OFC with 751 lines, bandwidth of 16.52 THz and flatness less than 2 dB.



(a)

(b)



(c)

(d)

Fig.5 In the case of multiple light sources, the spectra of generated OFCs with light numbers of (a) 4, (b) 12, (c) 20, and (d) 28 (The insets are the enlarged views of part of the spectra in (c) and (d), respectively.)

An ultra-wide, flat and tunable OFC generation scheme using multiple CW light sources based on EAMs and FM is proposed and investigated. The results show that in the case of a single light source, a flat and tunable OFC is obtained, and with the increase of line spacing, the line number reduces and the average power arises proportionally. With the increase of light sources, the bandwidth of generated ultra-wide OFC expands rapidly while the flatness deteriorates slightly. In the case of 28 light sources, an ultra-wide OFC with bandwidth of 16.52 THz and flatness smaller than 2 dB can be generated.

References

[1] Melo S A S, Optics Communications **312**, 287 (2014).

[2] Zhou X, Zheng XP, Wen H, Zhang HY, Guo YL and Zhou BK, Optics Communications **284**, 3706 (2011).

[3] Preussler S, Wenzel N and Schneider T, Optics Letters **39**, 1637 (2014).

[4] Shang L, Wen A, Lin G and Gao Y, Optics Communications **331**, 262 (2014).

[5] Zhou X, Zheng X, Wen H, Zhang HY and Zhou BK, Optics Communications **313**, 356 (2014).

[6] Zhang JW, Yu JJ, Chi N, Dong Z, Li XY, Shao YF, Yu JG and Tao L, Optics Letters **38**, 552 (2013).

[7] Li W, Wang WT, Sun WH, Wang LX, Liu JG and Zhu NH, Photonics Journal IEEE **6**, 205 (2014).

[8] Wang MG and Yao JP, IEEE Photonics Technology Letters **25**, 2035 (2013).

[9] Zhang X, Lin J, Xi L, Zhang XG and Bai CL, Optical Fiber Technology **20**, 116 (2014).

[10] Li Y, Wu S and Fei Y, Optik-International Journal for Light and Electron Optics **125**, 962 (2014).

[11] Morohashi I, Sakamoto T and Yamamoto N, Investigation of Linewidth of Comb Modes in MZM-based Flat Comb Generator with Optical Feedback Loop, 2012 Conference on IEEE Lasers and Electro-Optics (CLEO), 1 (2012).

[12] Ding Yongkui, Tan Li, Tian Hebin, Jia Dongfang and Li Shichen, Chinese Journal of Quantum Electronics **19**, 536 (2002). (in Chinese)