ЛАЗЕРНАЯ ФИЗИКА И ТЕХНИКА

ГЕНЕРАЦИЯ ОПТИЧЕСКОЙ ЧАСТОТНОЙ ГРЕБЕНКИ С ИСПОЛЬЗОВАНИЕМ НОВОЙ СХЕМЫ МОДУЛЯТОРА МАХА–ЦЕНДЕРА С ЧЕТЫРЬМЯ ПЛЕЧАМИ

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Предложен простой генератор оптической частотной гребенки на основе новой схемы модулятора Маха–Цендера, содержащей 1×4 многомодовый интерференционный разветвитель и четыре волноводных фазовых модулятора. Получена 25-тоновая генерация с амплитудными отклонениями в пределах 0,2 дБ и степенью подавления нежелательных мод в 27 дБ. Предложенный подход может позволить создать новое поколение генераторов оптических гребенок, обеспечивающих планарное исполнение.

AN OPTICAL FREQUENCY COMB GENERATION SCHEME USING A NOVEL MACH-ZEHNDER MODULATOR WITH FOUR ARMS

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We propose a simple and cost-effective ultra-flat optical frequency comb generator based on a novel Mach-Zehnder modulator which employs a 1×4 multimode interference coupler and four optical phase-modulator waveguides. 25-tone optical frequency comb with flatness within 0.2 dB and unwanted-mode suppression ratio of 27 dB is obtained. This approach may provide a new generation of combs that enable planar integration and may permit a direct link from the radio frequency to optical domain on a chip.

Key words: optical frequency comb, multimode interference coupler, radio-over-fiber, optical communications.

OCIS codes: 060.2330, 060.5625, 190.4160

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1. Introduction

Optical frequency comb (OFC) with equal frequency spacing, equal spectral intensity, and a great many of comb lines has received more and more attention, as it has many applications in optical communications such as arbitrary waveform generation, short optical pulse generation, dense wavelength division multiplexing and optical orthogonal frequency division multiplexing [1–5]. Many schemes have been proposed to generate flat and stable optical frequency comb, such as mode-locked lasers and externally modulating a single laser source with microwave signals. Nevertheless, the generated optical frequency comb based on mode locked lasers is usually not flat, and the frequency spacing between the lines is defined by the repetition rate of the laser [6]. OFC generation by externally modulating a single laser source with microwave signals is proved to be very economical. This method has many advantages including a simple configuration, adjustable wavelength, and precise comb spacing. The external modulator driven by a radio-frequency (RF) signal generates a series of sidebands which can be regarded as an OFC. To generate more comb lines, more modulators were used in the OFC generator. There are several methods that have been reported using Mach-Zehnder modulators (MZMs) and phase modulators [7–10]. In Ref. [7], as many as 9 lines within 2 dB power variation were obtained by two cascaded intensity modulators. Driven by tailored RF waveforms, the cascaded modulators could generate 38 tones within 1 dB spectral variation. But four modulators must be employed, and the applied RF signals must be tailored specially to generate a quadratic temporal phase [8]. With cascaded IM and PM, 15 lines within 1 dB power variation or 17 lines within 3 dB power variation were reported in Ref. [9]. In this scheme, the number of the comb lines is in direct proportion to the phase modulation index. A scheme using one intensity modulator and two phase modulators directly by sinusoidal waveform to generate an optical frequency comb was reported in Ref. [10], where 29 comb lines with spectral power variation less than 1.5 dB at 10 GHz were obtained. The number of modulators, however, must be increased to three, increasing also the cost. Recently 25 comb lines within 1 dB power variation were obtained by cascaded intensity modulator in Ref. [11].

In this paper, we propose a scheme using a novel MZM with four arms which employs a 1×4 multimode interference (MMI) coupler and four optical phase-modulator waveguides. Theoretical analysis and simulation results suggest that by adjusting the bias voltages and the power of the microwave signal of the MMI, we can achieve an OFC having 5 comb lines with the spectral flatness of 0.1 dB. When cascaded with another MMI, as many as 25 com lines with the spectral power variation less than 0.2 dB were obtained.

2. Analytical model

Multimode interference couplers have been intensively studied as splitting/recombining elements in integrated optics since they were firstly reported by Ulrich et al. [12]. Multimode interference couplers are employed as optical power splitters for dual-arm MZMs to generated optical SSB signal in ROF links. Furthermore, 1×N MMI couplers have prospects for MZMs with more than two arms, since MMI couplers do not need to be cascaded in large numbers to achieve large output port counts. In this paper, we propose a simple and cost-effective ultra-flat OFC generator based on a novel MZM which employs a 1×4 MMI coupler and four optical phase-modulator waveguides. The scheme of the 1×4 MMI coupler is shown in Fig. 1. It consists of an input mono-mode waveguide, a wide multimode section where the interference of modes occurs, and four output mono-mode waveguides which are denoted by i = 1, 2, 3, 4. The basic principle of MMI couplers is the self-imaging effect. The 1×4 MMI coupler splits the input light wave

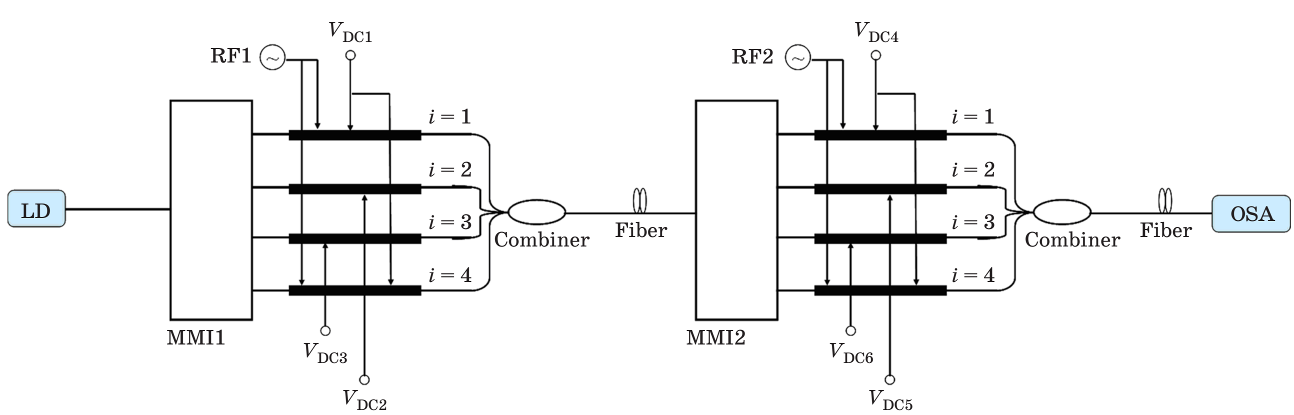

Fig. 1. Schematic diagram of the proposed optical frequency comb generator based on a novel MZM which employs a 1×4 MMI coupler and four optical phase-modulator waveguides. LD: laser diode. MMI: multimode interference, RF: radio frequency, DC: dc power supply, OSA: optical spectrum analyzer.

into four paths with equal intensities and different phases. The relative phases of the four optical paths are {0, π/2, π/2, 0} respectively. The 1×4 MMI coupler can be described by the following equation:

$$\begin{bmatrix} E_{\text{out}1}(t) \\ E_{\text{out}2}(t) \\ E_{\text{out}3}(t) \\ E_{\text{out}4}(t) \end{bmatrix} = \frac{1}{2}\begin{bmatrix} \exp(j0) \\ \exp\left(j\frac{\pi}{2}\right) \\ \exp\left(j\frac{\pi}{2}\right) \\ \exp(j0) \end{bmatrix} E_{\text{in}}(t). \quad (1)$$

Assume that the optical field of the continuous-wave (CW) laser is defined as $E_{\text{in}}(t) = E_0\cos(\omega t)$, where E_0 denotes the amplitude of the optical field, and ω is the angular frequency of the optical carrier. The light wave from a CW laser is split into four beams with equal intensities and different phases by the 1×4 MMI. The first branch and the fourth branch of the MMI cooperate to act as an intensity modulator. The MZM is driven by the electrical driving signal RF1 $V_{\text{RF1}}\sin(\omega_1 t)$, where V_{RF1} and ω_1 are the amplitude and the angular frequency of the input electrical signal, respectively. A DC voltage $2V_{\text{DC1}}$ is applied to the two arms of the MMI. Therefore the optical field at the output of the MZM is given by

$$\begin{aligned} E_{\text{out}}(t) &= \frac{1}{2}E_{\text{in}}(t)\exp\left[j\pi\frac{V_{DC1}+V_{\text{RF1}}\sin(\omega_1 t)}{V_\pi}\right] + \\ &+ \frac{1}{2}E_{\text{in}}(t)\exp\left[-j\pi\frac{V_{DC1}+V_{\text{RF1}}\sin(\omega_1 t)}{V_\pi}\right] = \\ &= \frac{E_{\text{in}}}{2}\sum_{n=-\infty}^{+\infty}\begin{bmatrix} J_n(m)\exp(jn\omega_1 t + j\varphi_1) + \\ + J_n(-m)\exp(jn\omega_1 t - j\varphi_1) \end{bmatrix}, \end{aligned} \quad (2)$$

where $J_n(\cdot)$ denotes the n^{th} order Bessel function of the first kind, $m = (\pi V_{\text{RF1}})/V_\pi$ is the RF modulation index, and $\varphi_1 = (\pi V_{\text{DC1}})/V_\pi$ is the phase shift caused by the DC voltage. We can get the expressions for the carriers,

$$\begin{aligned} E_{0,\,\text{MZM}} &= \frac{E_0}{2}J_0(m)\big(\exp(j\varphi_1)+\exp(-j\varphi_1)\big)\cos(\omega_1 t), \\ E_{\pm1,\,\text{MZM}} &= \pm\frac{E_0}{2}J_1(m)\big(\exp(j\varphi_1)-\exp(-j\varphi_1)\big)\times \\ &\times\cos[(\omega\pm\omega_1)t], \\ E_{\pm2,\,\text{MZM}} &= \frac{E_0}{2}J_2(m)\big(\exp(j\varphi_1)+\exp(-j\varphi_1)\big)\times \\ &\times\cos[(\omega\pm2\omega_1)t], \\ E_{\pm3,\,\text{MZM}} &= \frac{E_0}{2}J_3(m)\big(\exp(j\varphi_1)-\exp(-j\varphi_1)\big)\times \\ &\times\cos[(\omega\pm3\omega_1)t], \\ &\ldots \end{aligned} \quad (3)$$

If we let $|E_{\pm1,\,\text{MZM}}| = |E_{\pm2,\,\text{MZM}}|$, we can get

$$\begin{aligned} &\big|J_2(m)[\exp(j\varphi_1)+\exp(-j\varphi_1)]\big| = \\ &= \big|J_1(m)[\exp(j\varphi_1)-\exp(-j\varphi_1)]\big|. \end{aligned} \quad (4)$$

We can see that for any m, there exists always a proper φ that makes equation (4) true. Two DC voltages V_{DC2} and V_{DC3} are applied to the second and the third branches of the MMI respectively. The optical outputs of the two branches are $1/2E_0\exp(j\varphi_2)\cos(\omega t)$ and $1/2E_0\exp(j\varphi_3)\cos(\omega t)$, where $\varphi_2 = \pi V_{\text{DC2}}/V_\pi$ and $\varphi_3 = \pi V_{\text{DC3}}/V_\pi$. So the zero carrier of the output can be expressed as

$$\begin{aligned} E_{0,\,\text{MZM}} &= \frac{E_0}{2}J_0(m)\big(\exp(j\varphi_1)+\exp(-j\varphi_1)\big)\times \\ &\times\cos(\omega t)+\frac{1}{2}E_0\exp\left(j\frac{\pi}{2}\right)\exp(j\varphi_2)\cos(\omega t)+ \\ &+\frac{1}{2}E_0\exp\left(j\frac{\pi}{2}\right)\exp(j\varphi_3)\cos(\omega t). \end{aligned} \quad (5)$$

As can be seen from Eq. (5), by adjusting V_{DC2} and V_{DC3}, we can also realize $|E_{0,\,\text{MZM}}| = |E_{\pm1,\,\text{MZM}}| = |E_{\pm2,\,\text{MZM}}|$. For example, Eq. (4) and Eq. (5) are true when $m = 0.3\pi$, $\varphi_1 = 0.07\pi$, $\varphi_2 = 0.055\pi$, $\varphi_3 = 0.945\pi$. So, theoretically, an OFC with 5 exactly equal tones can be generated with the 1×4 MMI. In addition, according to the numerical values of Bessel functions of the first kind, when $0 < m < 0.851$, we can get $10\lg(J_1^2(m)/J_3^2(\text{m})) \geq 30$. That means that when $0 < m < 0.851$, $I_{\pm1}$ will be 30 dB higher than $I_{\pm3}$ and the other higher order sidebands.

When cascading with another 1×4 MMI which is with the same settings as the first MMI, the optical signal generated by the first MMI is sent to the second MMI. The angular frequency of RF2 is 5 times of that of RF1. Based on the same principle as described above, each spectral line can generate another 5 spectral lines by IM2. So we can get an optical frequency comb with 25-lines frequency comb.

3. Simulation results and discussions

Computer simulations with Virtual Photonics Inc. software package have been performed to study the performance of our proposed OFC generation technique. A CW laser with the linewidth

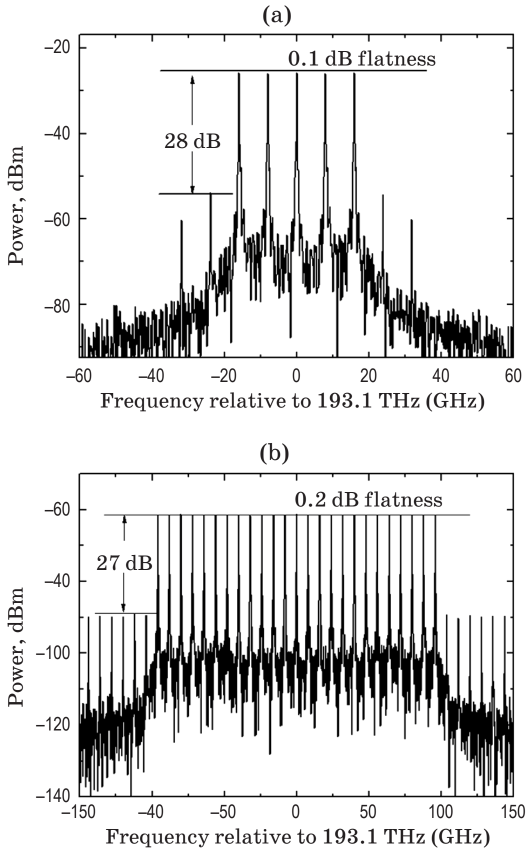

Fig. 2. Simulated output spectrum (a) 5-line frequency comb with a spacing of 8 GHz, (b) 25-line frequency comb with a spacing of 8 GHz.

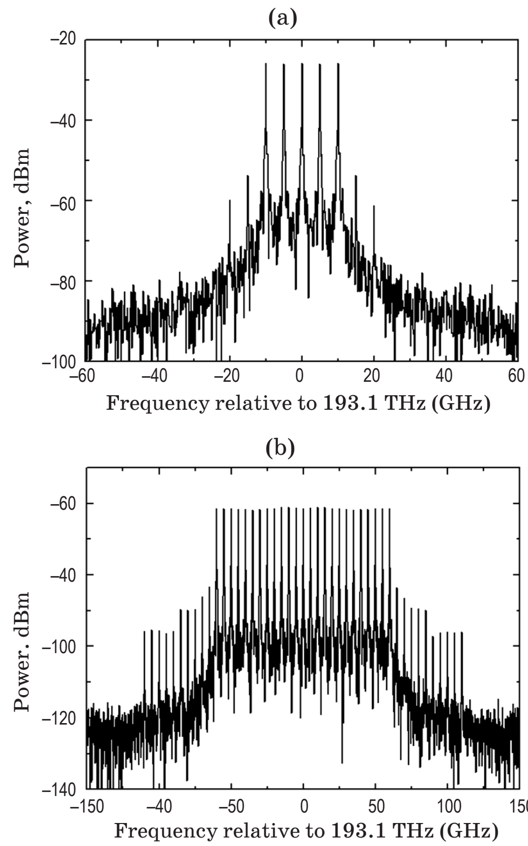

Fig. 3. Simulated output spectrum (a) 5-line frequency comb with a spacing of 5 GHz, (b) 25-line frequency comb with a spacing of 5 GHz.

of 10 MHz at the frequency of 193.1 THz is sent to the cascaded intensity modulators. The power of CW laser is 1 mW, the azimuth angle and the initial phase are equal to zero. The intensity modulators are with the same half-voltage of 3.5 V and the same extinction ratio of 30 dB. The frequency of RF1 we use is equal to 8 GHz. Based on the theoretical analysis, we set $m = 0.3\pi$, $\varphi_1 = 0.07\pi$, $\varphi_2 = 0.055\pi$, $\varphi_3 = 0.945\pi$. An OFC with 5 tones is generated at the output of MMI1 and is shown in Fig. 2a. The spectral flatness and out-band-suppression ratio are 0.1 and 28 dB respectively. When cascaded with MMI2, the frequency of RF2 we use is 40 GHz resulting in 25 comb lines with flatness of 0.2 dB and frequency spacing 8 GHz (Fig. 2b). The out-band-suppression ratio is 27 dB.

This method for OFC generation is simple and adjustable, and the frequency spacing is determined by the frequency of the RF signal. As an example, Figs. 3a and 3b show the 5 and 25 lines comb respectively, with frequency spacing equal to 5 GHz.

4. Conclusion

A simple and cost-effective ultra-flat OFC generator was proposed and investigated, based on a novel MZM which employs a 1×4 MMI coupler and four optical phase-modulator waveguides. 25-tone OFC with flatness within 0.2 dB and unwanted-mode suppression ratio of 27 dB is obtained. This approach provides a new generation of combs that enable planar integration and permits a direct link from the RF to optical domain on a chip.

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ЛИТЕРАТУРА

1. *Morioka T., Mori K., Saruwatari M.* More than 100-wavelength-channel picosecond optical pulse generation from single laser source using supercontinuum in optical fibres // Electron. Lett. 1993. V. 29. P. 862.
2. *Okamoto K., Kominato T., Yamada H., Goh T.* Fabrication of frequency spectrum synthesiser consisting of arrayed-waveguide grating pair and thermo-optic amplitude and phase controllers // Electron. Lett. 1999. V. 35. P. 733.
3. *Bennett S., Cai B., Burr E., Gough O., Seeds A.J.* 1.8-THz bandwidth, zero-frequency error, tunable optical comb generator for DWDM applications // IEEE Photon. Technol. Lett. 1999. V. 11. P. 551.
4. *Fontaine N.K., Geisler D.J., Scott R.P., He T., Heritage J.P., Yoo S.J.B.* Demonstration of high-fidelity dynamic optical arbitrary waveform generation // Opt. Exp. 2010. V. 18. P. 22988.
5. *Jiang Z., Huang C.B., Leaird D., Weiner A.M.* Optical arbitrary waveform processing of more than 100 spectral comb lines // Nature Photon. 2007. V. 1. P. 463.
6. *Jiang Z., Leaird D.E., Weiner A.W.* Spectral line-by-line pulse shaping on an optical frequency comb generator // IEEE Quantum Electron. 2007. V. 43. P. 1163.
7. *Fujiwara M., Kani J., Suzuki H., Araya K., Teshima M.* Flattened optical multicarrier generation of 12.5 GHz spaced 256 channels based on sinusoidal amplitude and phase hybrid modulation // Electron. Lett. 2001. V. 37. P. 967.
8. *Wu R., Supradeepa V.R., Long C.M., Leaird D.E., Weiner A.M.* Generation of very at optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms // Opt. Lett. 2010. V. 35. P. 3234.
9. *Dou Y., Zhang H., Yao M.* Improvement of flatness of optical frequency comb based on nonlinear effect of intensity modulator // Opt. Lett. 2011. V. 36. P. 2749.
10. *Dou Y., Zhang H., Yao M.* Generation of flat optical-frequency comb using cascaded intensity and phase modulators // IEEE Photon. Technol. Lett. 2012. V. 24. P. 727.
11. *Shang L., Wen A.J., Lin G.B.* Optical frequency comb generation using two cascaded intensity modulators // J. Opt. 2014. V. 16. P. 035401.
12. *Ulrich R., Ankele G.* Self imaging in homogeneous planar optical waveguides // Appl. Phys. Lett. 1975. V. 27. P.337.