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Self-oscillating frequency comb generation with a stimulated Brillouin scattering based optoelectronic oscillator

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ABSTRACT

A self-oscillating optical frequency comb (OFC) generator based on an electrical filter-free optoelectronic oscillator (OEO) is proposed and experimental demonstrated. By using stimulated Brillouin scattering (SBS) in a fiber, phase-modulation to intensity-modulation conversion is achieved to realize an oscillation in a loop. The generated oscillation signal has a frequency equal to a Brillouin frequency shift in the fiber, and it is used to drive another phase modulator to generate OFC lines. A 9-tone frequency comb is demonstrated with a power variation of 3 dB, and the single-sideband phase noise of the OEO is measured to be −80 dBc/Hz at 10 kHz offset frequency.

1. Introduction

Optical frequency comb (OFC) generation is attractive in many applications such as optical frequency measurement [1], optical arbitrary waveform generation (O-AWG) [2], wavelength division multiplexing (WDM) networks [3], microwave photonics [4] and so on [5]. Up to now, there are three ways commonly used to generate OFCs, i.e. the methods respectively based on mode-locked lasers [6], electro-optical modulation (EOM) [7] and nonlinearities [8]. Among these methods, the EOM scheme has drawn more attention owing to its advantages of adjustability, stability and large bandwidth [9]. However, an external microwave signal source is required to drive electro-optical intensity and/or phase modulators, and the phase noise of the generated comb line, especially the higher order lines, is determined by the performance of the signal source [10]. Consequently, some schemes for self-oscillating OFC generation have been proposed. In [11], an optoelectronic oscillator (OEO) is achieved by asymmetric filtering phase modulated light wave with a fiber Bragg grating (FBG). In the oscillator cavity, a phase modulator (PM) is driven by the lager-amplitude feedback signal, so an OFC with a 120 GHz bandwidth and 9.95 GHz frequency spacing is generated [11]. Based on an OEO using cascaded electro-optical intensity modulator (IM) and PM, 11-line OFCs are also demonstrated with a frequency spacing equal to 10 GHz and 12 GHz respectively in [12]. For the above two schemes, an electronic band-pass filter (EBPF) is required to realize a single-mode oscillator. Alternatively, a band-pass microwave photonic filter (MPF) can also be applied in an OEO to select the oscillation mode and release the use of EBPF. In [13], a polarization modulator (PolM), a phase-shifted FBG (PS-FBG) and a photo-detector (PD) are used working as a band-pass MPF in an oscillating loop, and a 9-line OFC is achieved by driving a second PolM with the oscillation signal. Another more attractive method for releasing the use of EBPF in OEOs is to employ simulated Brillouin scattering (SBS) owing to its low threshold and narrow gain bandwidth within tens of megahertz [14]. In [15], a Brillouin optoelectronic filter with a subhertz linewidth for RF signals is implemented, and with this filter the low frequency phase noise of the output signal below 1 kHz offset has an improvement of about 10 dB over that of the input RF signal [15]. By tuning the wavelength of the signal or the pump laser, wideband tunable OEOs have been realized with Brillouin process acting as a sideband amplifier with a narrow bandwidth [16,17]. In the similar way, a tunable multi-frequency OEO has also been demonstrated [18]. To build a self-oscillating optical comb generator, a SBS-based OEO is designed [19]. In this generator, a Raman pump is also applied to provide flat optical gain to the comb lines. And a 7-line OFC with 10.89 GHz frequency spacing and 2.7 dB power variation is obtained.

In this work, we also propose a self-oscillating OFC generator with an electrical filter-free OEO which is achieved by Brillouin amplification of phase modulated light wave. And single one CW laser is used without any other pump source. The generated oscillation signal is employed to drive another PM to obtain more comb lines. In the experiments, a 9-line OFC with 10.87 GHz frequency spacing and 3 dB power variation is achieved, and for the OEO, the single-side band (SSB) phase noise is about −80 dBc/Hz @ 10 kHz offset.

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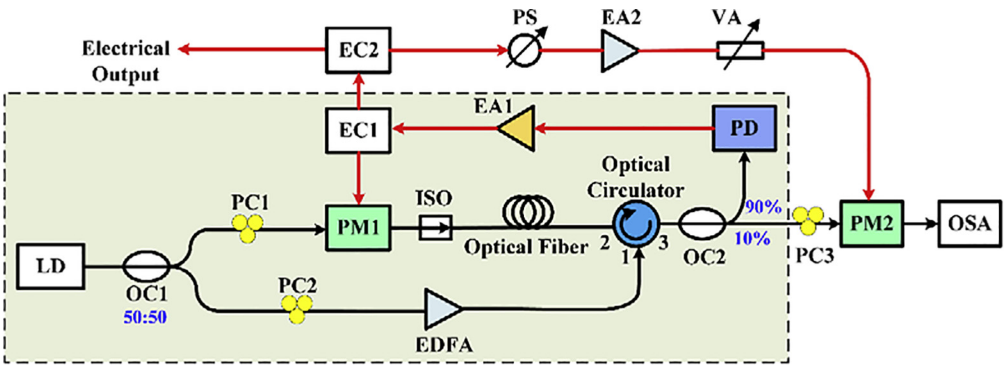

Fig. 1. Schematic diagram of the proposed OFC generator with SBS based OEO. (OC: Optical coupler; PC: Polarization controller; PM: Phase modulator; ISO: Optical isolator; EDFA: Erbium doped fiber amplifier; OSA: Optical spectrum analyzer; PD: Photo-detector; EA: Electrical amplifier; EC: Electrical coupler; PS: Phase shifter; VA: Variable attenuator).

2. Principle

The system architecture of the proposed self-oscillating OFC generator is shown in Fig. 1. A CW light with a frequency of f_c from the laser diode is divided into two paths via an optical coupler (OC1). In the lower branch, the light wave is amplified by an Erbium-doped fiber amplifier (EDFA) and injected into port-1 of an optical circulator to stimulate Brillouin scattering process in a spool of fiber. In the upper branch, the light wave is phase modulated and launched into the fiber. To eliminate the unavoidable feedback, an optical isolator (ISO) is inserted between the phase modulator (PM) and the fiber. When the -1st noise-based sideband is located in Brillouin gain region, it is amplified and the phase-modulation to intensity-modulation conversion is achieved [20]. The beat signal between carrier wave and -1st sideband through the photodiode is amplified by an electronic amplifier (EA) and fed back to the PM to form a closed loop oscillation. The final oscillation mode is the generated microwave signal and it has a central frequency equal to a Brillouin frequency shift, f_B in the fiber. In our scheme, a portion of the oscillating signal is amplified to drive another PM to generate more comb lines. The flatness of the generated OFC can be improved by adjusting the RF phase shifter (PS) and the variable attenuator (VA).

Mathematically, for the case of small signal modulation, the normalized optical field $E_{out\_PM1}(t)$ at the output of PM1 can be expressed as,

$$E_{out\_PM1}(t) = E_0\exp(j2\pi f_c t)[J_0(m_1) + J_1(m_1)\exp(j2\pi f_m t) - J_1(m_1)\exp(-j2\pi f_m t)] \quad (1)$$

where $E_0\exp(j2\pi f_c t)$ is the input optical field from the laser, $J_n(.)$ denotes the nth-order Bessel function of the first kind with $n = 0$ or 1, $m_1 = \pi V_1/V_{\pi1}$ is the modulation depth of PM1, V_1 is the amplitude of the driving signal, $V_{\pi1}$ is the half-wave voltage of PM1, and f_m is the frequency of the oscillating signal. When $f_m = f_B$, the -1st sideband of the phase modulated laser is located in the Brillouin gain region. The Brillouin amplified signal can be expressed as

$$E_{out\_fiber}(t) = E_0\exp(j2\pi f_c t)[J_0(m_1) + J_1(m_1)\exp(j2\pi f_B t) - \sqrt{G}J_1(m_1)\exp[-j(2\pi f_B t + \varphi)]] \quad (2)$$

where G and φ are respectively the gain and phase shift induced by Brillouin amplification. And they are determined by the Lorentzian gain profile $g_B(f)$ of the Brillouin process in the fiber [21].

$$g_B(f) = \frac{g_0 P_P L_{eff}}{2A_{eff}}\frac{(\gamma_B/2)^2}{f^2 + (\gamma_B/2)^2} + j\frac{g_0 P_P L_{eff}}{4A_{eff}}\frac{\gamma_B f}{f^2 + (\gamma_B/2)^2} \quad (3)$$

where g_0 and γ_B represent the center gain factor and Brillouin linewidth of the fiber, P_p is the pump power of the wave, $L_{eff} = [1-\exp(-\alpha L)]/\alpha$ is the effective fiber length, α, L and A_{eff} are respectively the loss coefficient, length and effective area of the fiber, and f denotes the frequency offset to the carrier.

After PD, the generated photo-current is

$$I_o(t) = 2P_0RJ_0(m_1)J_1(m_1)[\cos 2\pi f_B t - \sqrt{G}\cos(2\pi f_B t + \varphi)] = 2P_0RJ_0(m_1)J_1(m_1)\sqrt{G + 1 - 2\sqrt{G}\cos\varphi}\,\sin(2\pi f_B t - \xi) \quad (4)$$

where the dc and double RF frequency components are neglected, $P_0 = |E_0|^2$, R is the responsivity of PD, and $\xi = \tan^{-1}\left(\frac{\sqrt{G}\cos\varphi - 1}{\sqrt{G}\sin\varphi}\right)$. The total optical link gain is expressed as

$$G_o = \frac{\pi^2 P_0^2 R^2 Z_0^2 (G + 1 - 2\sqrt{G}\cos\varphi)}{2V_{\pi1}^2} \quad (5)$$

where $J_0(m_1) \approx 1$, $J_1(m_1) \approx m_1/2$ for small signal approximation, and Z_0 is the resistance of PD. In order to maintain the oscillation, the gain in the loop should satisfy $G_o \cdot G_e > 1$. Here G_e is the total electrical gain, and it should be

$$G_e > \frac{2V_{\pi1}^2}{\pi^2 P_0^2 R^2 Z_0^2 (G + 1 - 2\sqrt{G}\cos\varphi)} \quad (6)$$

As shown in Fig. 1, a portion of the optical field at the output of the fiber is again phase modulated by the oscillation signal. So, the output of PM2 can be shown as

$$E_{out\_PM2}(t) = E_{out\_fiber}(t)\exp[jm_2\cos(2\pi f_B t + \theta)] \quad (7)$$

where $m_2 = \pi V_2/V_{\pi2}$ is the modulation depth of PM2, V_2 is the amplitude of the driving signal, $V_{\pi2}$ is the half-wave voltage of PM2, and θ is the relative phase shift between the signals driving PM1 and PM2.

From the analysis presented above, we can find that the generated spectrum at the output of PM2 is determined by Eqs. (2), (3) and (7). To generate flat-topped combs, we investigate the impacts of $m_{1,2}$ and θ on the output spectra. In our study, a 4-km single mode fiber (SMF) is employed to stimulate SBS process, and the pump power is set to be 12 dBm. Also a set of typical values for SMF parameters is used, such as $A_{eff} = 100\,\mu m^2$, $\alpha = 0.2$ dB/km, $\gamma_B = 20$ MHz and $g_0 = 1 \times 10^{-11}$ m/W. Fig. 2(a) and (b) show the results for the case when a 9-tone comb is output, where the Z-axes represent the power deviation of the output comb lines using dB as a unit. From Fig. 2 (a), it can be seen that a 9-line target spectrum with a power variation less than 6 dB can be achieved by adjusting $m_{1,2}$ with $\theta = \pi/2$. In this case, the required modulation depth m_1 is less than 0.8π, and m_2 less than 1.3π. When $m_1 = \pi$, flat-topped OFC can also be obtained with m_2 less than 1.1π and θ equal to about 1.5π, as shown in Fig. 2(b).

3. Experimental results and discussion

A proof of concept experiment of the proposed OFC generator based on the setup shown in Fig. 1 is performed. The central wavelength of the CW laser is 1548.95 nm and the output power is 12 dBm. PM1 and PM2 have a bandwidth of 10 GHz and a half-wave voltage equal to 3.5 V. In the loop, the length of SMF is 4 km. The Brillouin frequency shift of the SMF is measured to be 10.87 GHz. In the lower path, the amplified laser with a power about 15dBm is injected in the opposite direction to the SMF to stimulate SBS process. 90% of the output optical