Self-oscillating optical comb generator based on optoelectronic oscillator

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ABSTRACT

This work is focused on two promising concepts of microwave photonics- optoelectronic oscillators and optical frequency comb generators, and their use to generate a self-oscillating optical comb. In particular we develop a recirculating loop topology in which a Mach-Zehnder modulator is modulated recursively via a secondary loop that acts as a self-homodyne input.

Keywords: Optoelectronic oscillator, Optical frequency comb generation, Phase noise, Mach-Zehnder modulator.

1. INTRODUCTION

The optoelectronic oscillator (OEO) has attracted intense interest in microwave photonics research since the mid- 1990's due to its relatively stable and superior spectral purity performance compared to conventional microwave oscillators such as those based on dielectric resonators [1]. The spectral purity provided by OEOs is directly correlated to usage of high Q optical storage elements such as long lengths of optical fibre and the recently introduced whispering gallery mode resonator (WGMR) [2, 3]. Compared with techniques based on injection locking, phase-locked loops or external modulation, the use of an OEO can generate a microwave signal without the need for a reference microwave source [4]. The basic topology of an OEO consists of a single closed hybrid loop containing an optical path (typically several km of single mode fiber which acts as an energy storage element) and a microwave path (typically containing an amplifier, band pass filter and RF output coupler).

The optical frequency comb generator (OFCG) is a very convenient way to generate a number of phase-correlated optical carriers with accurate frequency spacing. It is a useful tool for various applications in microwave and millimeter wave photonic technologies including optical and microwave waveform generation, optical signal processing, and fiber optic communication [5]. Optical frequency combs are especially useful for the latest generation of optical multicarrier communication systems, where information is encoded onto so-called super channels [6]. The key figures of merit for OFCGs are high coherence, high stability, low noise, high efficiency, low cost, simplicity and good spectral flatness (i.e. each optical frequency component should ideally have the same intensity [7]). Several approaches have been demonstrated theoretically and experimentally for the generation of optical combs. Conventionally, mode-locked lasers, fiber nonlinearities and external modulation are the principle methods for OFC generation.

Self-oscillating optical frequency comb generation is a promising concept which combines two emerging techniques in microwave photonics, namely optical frequency comb generation and optoelectronic oscillators. Several schemes have been reported to generate self oscillating optical frequency comb. In [8] T. Sakamoto *et. al*. proposed a self oscillating optical frequency comb based on an OEO loop employing a lithium niobate phase modulator and fibre Bragg grating (FBG) filter. The reported SOFCG in [8] provided a bandwidth of 120 GHz with a frequency spacing of 9.95 GHz. A tunable optical frequency comb generation based on an optoelectronic oscillator is reported in [9]. A wideband larger than 40 nm with a frequency spacing of 25 GHz and single side band phase noise (SSB) of -122 dBc/Hz at 10 Khz offset by incorporating a commercially available integrated OFCG (OptoComb Inc.) in the OEO loop was reported in [10]. In [11] an ultra flat OFCG based on an OEO loop employing an intensity modulator and a phase modulator in cascade was demonstrated experimentally. The reported SOFCG exhibited 11 flat top lines whose spectral flatness was within 0.82 dB and 0.93 dB when the comb spacing was 10 GHz and 12 GHz respectively.

In this paper, we propose and report simulation results of an OEO-based optical frequency comb generator without using an external microwave frequency synthesizer. A frequency comb generator section (based on an optical feedback loop) is inserted in an OEO loop to realize the SOFCG. The OEO is used to generate a reference microwave source which determines the frequency spacing of the generated comb lines. Thus, a wideband optical frequency comb and low phase noise microwave signal can be generated simultaneously during the OEO's oscillation. To validate the concept, a SOFCG model is proposed and analyzed using the commercially available VPItransmissionMaker^{TM} simulation package. The model predicts seven comb lines covering a band width of 35 GHz with a power variation of 20 dB and comb spacing of 5 GHz.
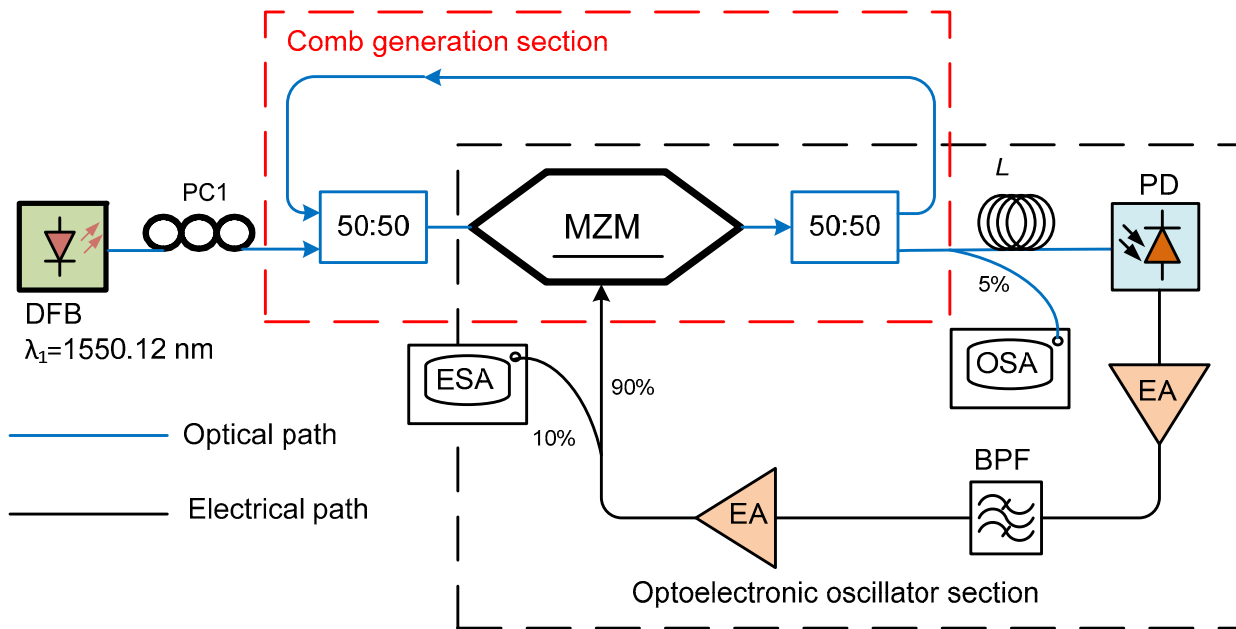

Figure 1. Basic operation principle of the proposed self-oscillating optical frequency comb generator.

2. PROPOSED CONCEPT

The proposed self-oscillating optical frequency comb generator (SOFCG) is shown in Fig. 1. The SOFCG consists of two subsystems: an OFCG and OEO. The OFCG section is based on an optical feedback loop. It includes the laser diode (LD), dual-drive Mach Zehnder modulator (DDMZM), two 50:50 couplers and an optical feedback loop. The first 50:50 coupler before the DDMZM termed a pre-coupler while the second coupler after the DDMZM is a post-coupler. The OEO section is composed of a single hybrid loop containing a LD, DDMZM, single mode optical fibre (SMF) of length L, photodiode (PD), electrical amplifier (EA) and band-pass filter (BPF).

A quadrature-biased dual drive Mach-Zehnder modulator (DDMZM) is fed by a CW light source from a distributed feedback laser (DFB) via the pre-coupler. The modulated output from the DDMZM is split into two paths by the post-coupler. One signal path is used for comb generation while the other is used for the OEO loop. The optical signal that is used for the OEO loop is further divided by a 95:5 optical coupler in order to allow monitoring via an optical spectrum analyzer (OSA). The other output is delayed by a fiber of length L prior to entering a high-speed photodiode (PD) and a low-noise amplifier (EA). The SMF is used to improve the Q factor of the self oscillating loop. The high-speed photo detector converts the optical signal to the electrical domain and the electrical signal is connected to the RF port of the DDMZM after passing through an electrical band-pass filter and low noise amplifier. The electrical band-pass filter is used to select the oscillating frequency of the optoelectronic section which also determines the comb separation. The amplifier stages are used to compensate the loss of the opto-electronic feedback loop and to meet the oscillation condition. Before connecting the microwave signal to the modulator's RF port, the signal is divided by a 90:10 microwave coupler to allow measurement of spectrum of the oscillating microwave signal with an electrical spectrum analyzer (ESA). The second output from the post-coupler is connected to the pre-coupler through an optical path where

another input of the pre-coupler is taken from seed laser source. Thus, the modulated output of the DDMZM is re-modulated since a portion of the modulated signal is connected via an optical feedback loop. The optical feedback loop that provides the optical frequency comb can be modeled as cascaded modulation system in which a series of MZMs successively modulate the input lightwave [12]. To reduce the polarization dependent loss, a polarization controller is also used before the pre-coupler.

3. SIMULATION SETUP

The proposed concept has been simulated with VPItransmissionMaker[TM] software. The schematic layout of the model with realistic parameter values is depicted in Fig.2 for the self-oscillating optical comb as described above. The DFB laser is modeled by a single-mode rate-equation based semiconductor laser (SM-RE). The optical output power of SM-RE is 17 mW at a wavelength of 1550 nm. The output optical signal is fed to a 3 dB 4-port directional coupler which is modelled by a cross coupler with coupling coefficient 0.5. Another input of the cross coupler is provided from the output of a fork module which is placed after a quadrature-biased dual drive MZM with V_π = 5 V, optical insertion loss 5 dB, and extinction ratio 35dB. A delay signal unit is used to realize the single mode fibre (SMF) section of Fig.1. The delay time is fixed to τ = 314.4 ns which is equivalent to a fibre length of 65m. An attenuator is used to characterize the loss of the optical fibre and fibre to other devices coupling loss. A PIN photodiode (PD) model is used as an optical to electrical converter with responsivity 0.8 A/W. Thermal noise, dark current and shot noise parameters are enabled during simulation to represent the noise characteristics of the PD. A band-pass filter (BPD) is represented by a fourth order Butterworth filter with a center frequency of 5 GHz and 3-dB bandwidth of 12 MHz. The center frequency of the BPF determines the gain bandwidth of the OEO loop and hence determines the oscillation frequency and comb spacing. The low noise amplifier (LNA) and power amplifier (PA) section of Fig.1 are realized with an electrical amplifier module. Two electrical amplifier stages are used during the simulation each with a 20 dB gain.
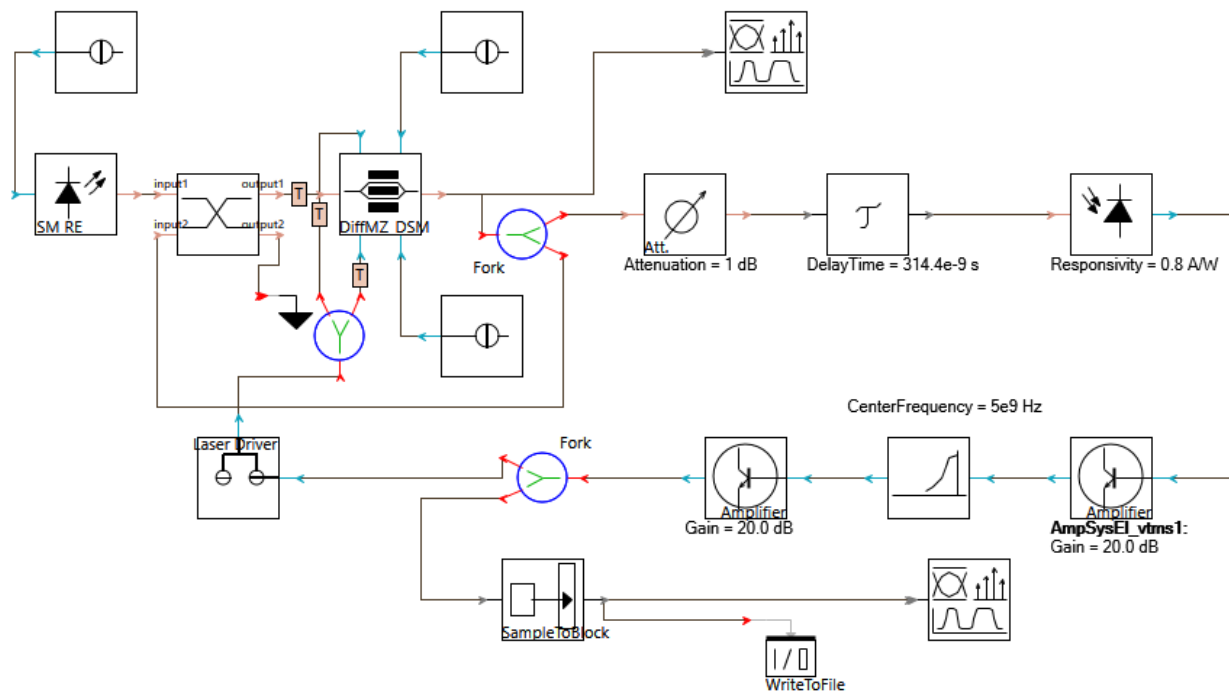

Figure 2. Schematic of SOFCG using the VPItransmissionMaker[TM] software.

The simulation model is executed with a periodic boundary condition with a default time window equal to 32786/bit rate, where the bit rate default = 5 Gb/s. In VPItransmissionMaker[TM] periodic boundary conditions allow parallel simulation of the RF and optical elements [13]. The time window determines the frequency resolution of the signal analyzer and the frequency resolution is inversely proportional to the time window [14].
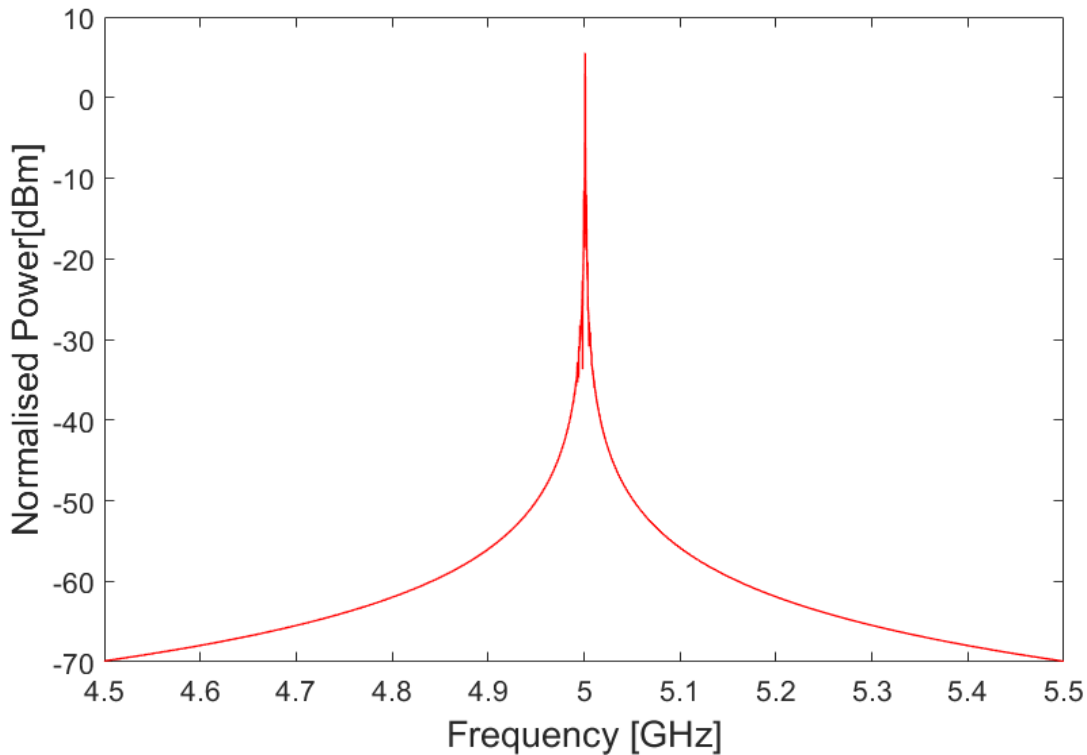
Figure 3. Electrical spectrum of the generated oscillation at 5 GHz.

4. RESULTS AND DISCUSSION

In this section, we present the simulation results of our proposed system which was obtained using the VPItransmissionMaker[TM] commercial software. We set the parameters of the different electrical and optical components as described in the simulation setup sections. Initially we set the electrical amplifier gain to a relatively low value and we observed that there was no oscillation due to insufficient gain in the OEO loop. Then, we set the electrical amplifier gain to a relatively high value and we observed that there were many modes in the oscillation spectrum due to the broad gain bandwidth available. Finally, we set the amplifier gain to a value for which only one mode oscillates. We set the center frequency of the electrical band-pass filter as 5 GHz with a 3 dB bandwidth of 12 MHz. Figure 3 shows the electrical spectrum of the generated oscillation signal at 5 GHz with a span of 1 GHz. The normalized power of the 5 GHz oscillation signal is 7 dBm. The optical spectrum of the generated optical frequency comb is shown in Figure 4. The comb spacing is 5 GHz, which is equal to the oscillation frequency of the single loop OEO section. The SOFCG provides seven comb lines covering a bandwidth of 30 GHz and the flatness of the comb lines is within 20 dB.

Carrier power to noise power density ratio (CNR) is an important parameter which should be as large as possible for reliable transmission of information. The CNR is defined as the ratio of the carrier power P_c and the noise power density N_o at the position of the carrier:

$$CNR \quad [\text{dBHz}] = 10 \log_{10} \left(\frac{P_c}{N_o \Delta f} \right) \quad . \quad\quad (1)$$

Here, the noise power density N_o is normalized to a bandwidth of $\Delta f = 1$ Hz. As seen in Fig. 4 the CNR of the spectrum is larger than 75 dBHz at a reference bandwidth of 1 Hz.
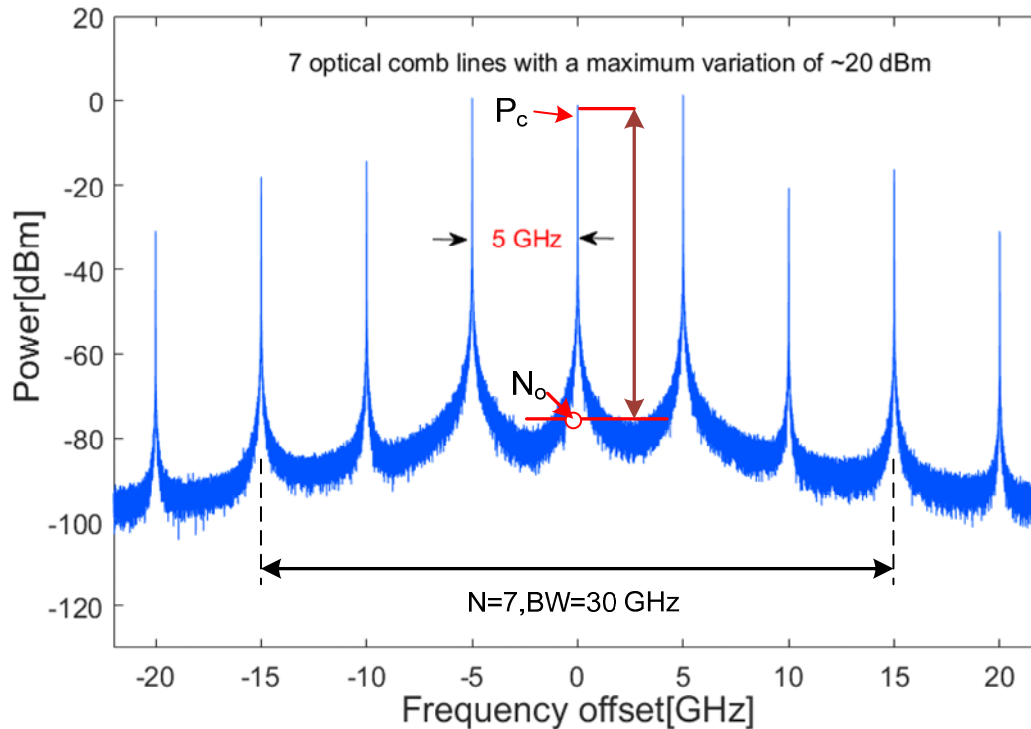
Figure 4. Spectrum of optical comb.

5. CONCLUSION

We have investigated a model of a self-oscillating optical frequency comb generator using an optical feedback loop based optical comb generator and OEO. The generated comb spacing is 5 GHz and 7 optical comb lines are generated covering a bandwidth of 35 GHz. The power variation of the seven comb lines is within 20 dB. The generated SOFCG represents an all-photonic approach for generating microwave and millimeter wave signals (without an RF reference source) and have the potential to be applied to radio-over-fiber links.

ACKNOWLEGEMENT

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