Optics Communications 331 (2014) 262–266

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A flat and broadband optical frequency comb with tunable bandwidth and frequency spacing

Lei Shang*, Aijun Wen, Guibin Lin, Yongsheng Gao

Department of Telecommunications Engineering, State Key Laboratory on Integrated Services Networks, Xidian University, Xi'an 710071, China

ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form
5 June 2014
Accepted 16 June 2014
Available online 26 June 2014

Keywords:
Optical frequency comb (OFC)
Intensity modulator
Optical communications

ABSTRACT

A flat and broadband optical frequency comb generator based on two cascaded intensity modulators is proposed and experimentally demonstrated. In this scheme, we first use even or odd harmonic sidebands to generate optical frequency comb, so the bandwidth can be improved. By adjusting the power of the microwave signals and the direct current bias applied to the modulators, a flat and broadband optical frequency comb can be achieved. The scheme is relatively simple and adjustable, where the frequencies spacing vary with microwave frequency applied on modulators. 15 and 20 comb lines with the comb flatness within 1 dB can be generated. The generated spectrums can meet the requirement of OFDM modulation, and can be used for high capacity optical transmission systems in the future.

1. Introduction

Optical frequency comb (OFC) has many applications in optical communications such as dense wavelength division multiplexing, optical orthogonal frequency division multiplexing, short optical pulse generation and arbitrary waveform generation [1–4]. In such applications the number of comb lines, bandwidth, spectral flatness and optical tone-to-noise ratio (OTNR) represents key considerations. A number of approaches have been proposed for optical frequency comb generation. Mode-locked lasers referenced to an external or internal optical reference can generate optical frequency combs with large bandwidth and high stability. However, this scheme always needs sophisticated control to achieve stable operation, and the center wavelength and frequency spacing are difficult to tune over a wide range [5]. A novel method for optical frequency comb generation by nonlinear wave mixing in a microresonator has been reported. The essential advantages of this comb generation method are its small size and very high repetition rate [6]. OFC generation by externally modulating a single laser source with microwave signals is proved to be very economical. Advantages of this method include the simple configuration, stable operation, adjustable wavelength, and precise comb spacing. There are several methods that have been reported using Mach–Zehnder modulators and phase modulators [7–9]. To generate more comb lines, more modulators were used in the OFC generator, and the bandwidth of the OFC is limited by the modulation bandwidth of the modulator. Driven by tailored RF waveforms, the cascaded modulators can generate 38 tones within 1 dB spectral variation. But four modulators must be employed and the applied radio frequency (RF) signals must be tailored specially to generate a quadratic temporal phase [7]. With cascaded IM and PM, 15 lines within 1 dB power variation or 17 lines within 3 dB power variation were reported in Ref. [8]. In this scheme, the number of the comb lines is in direct proportion to phase modulation index. But one phase modulator cannot be applied too large amplitude of sinusoidal waveform. A scheme using one intensity modulator and two phase modulators directly by sinusoidal waveform to generate an optical frequency comb is reported in Ref. [9]. 29 comb lines with spectral power variation less than 1.5 dB at 10 GHz were obtained. But three modulators must be employed, which make the cost increased. Recently 25 comb lines within 1 dB power variation were obtained by two cascaded intensity modulators in Ref. [10]. But the bandwidth of the OFC is only four times of the frequency of the first microwave signal. A 10 GHz comb with 20 comb lines within 0.6 dB spectral power variation can be achieved using two cascaded intensity modulators and one single dual-parallel modulator in Ref. [11], but three modulators must be employed, so the cost can be increased. However, the bandwidth of the OFC generated by externally modulating a continuous-wave (CW) laser source is limited by the restricted modulation bandwidth of the modulators.

In this letter, we propose and experimentally demonstrate one novel scheme composed of two cascaded intensity modulators to generate a flat and broadband optical frequency comb. Even or odd harmonic sidebands are used to generate optical frequency comb to improve the bandwidth, which can extend the bandwidth of the

* Corresponding author.
E-mail address: lshang@xidian.edu.cn (L. Shang).

http://dx.doi.org/10.1016/j.optcom.2014.06.029
0030-4018/

optical frequency comb. When the first intensity modulator is biased at its minimum transmission point, optical carrier and all even harmonic sidebands are suppressed. By adjusting the power of the microwave signal applied to the first intensity modulator, the amplitudes of the ± 3th harmonic and the ± 1th harmonic are equal. So we can achieve an OFC with 4 comb lines and the bandwidth of the OFC is 6 times of the frequency of the microwave signal. When the first intensity modulator is biased at its maximum transmission point, all odd harmonic sidebands are suppressed. By adjusting the power of the microwave signal applied to the first intensity modulator, the amplitudes of the ± 2th harmonic and the optical carrier harmonic are equal. An OFC with 3 comb lines can be achieved and the bandwidth of the OFC is 4 times of the frequency of the microwave signal. When cascading with another intensity modulator, the optical signal generated by IM1 is sent to IM2. By carefully adjusting the DC bias and the drive amplitudes of the RF signals of IM2, each comb line generated from IM1 will split to be 5 spectral lines after IM2. So an optical frequency comb can be generated with a flexible number of comb lines such as 15 and 20.

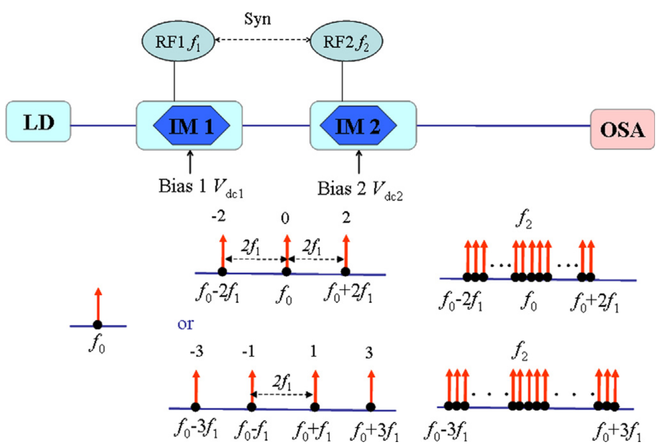

Fig. 1. Schematic diagram of the proposed optical frequency comb generator based on cascaded intensity modulators. LD: laser diode. IM: intensity modulator. RF: radio frequency. DC: dc power supply. OSA: optical spectrum analyzer.

2. Principle of analytical model

The schematic diagram of the proposed optical frequency comb generator which is performed using two cascaded Mach–Zehnder intensity modulators is shown in Fig. 1. To scale the bandwidth of the comb, we set IM1 biased at its minimum transmission point, and optical carrier and all even harmonic sidebands are suppressed. By adjusting the power of the microwave signal applied to the first intensity modulator, the amplitudes of the ± 3th harmonic and the ± 1th harmonic are equal. So we can achieve an OFC with 4 comb lines and the bandwidth of the OFC is six times of the frequency of the microwave signal. Assume that the field of optical source is defined as $E_{in}(t) = E_0 \cos(\omega_0 t)$, where E_0 denotes the amplitude of the optical field, and ω_0 is the angular frequency of the optical carrier. An electrical RF driving signal $V_1(t) = V_1 \sin(\omega_1 t)$ is applied to IM1, where V_1 and ω_1 are the corresponding amplitude and frequency of the microwave signal. When the first intensity modulator is biased at its minimum trans-

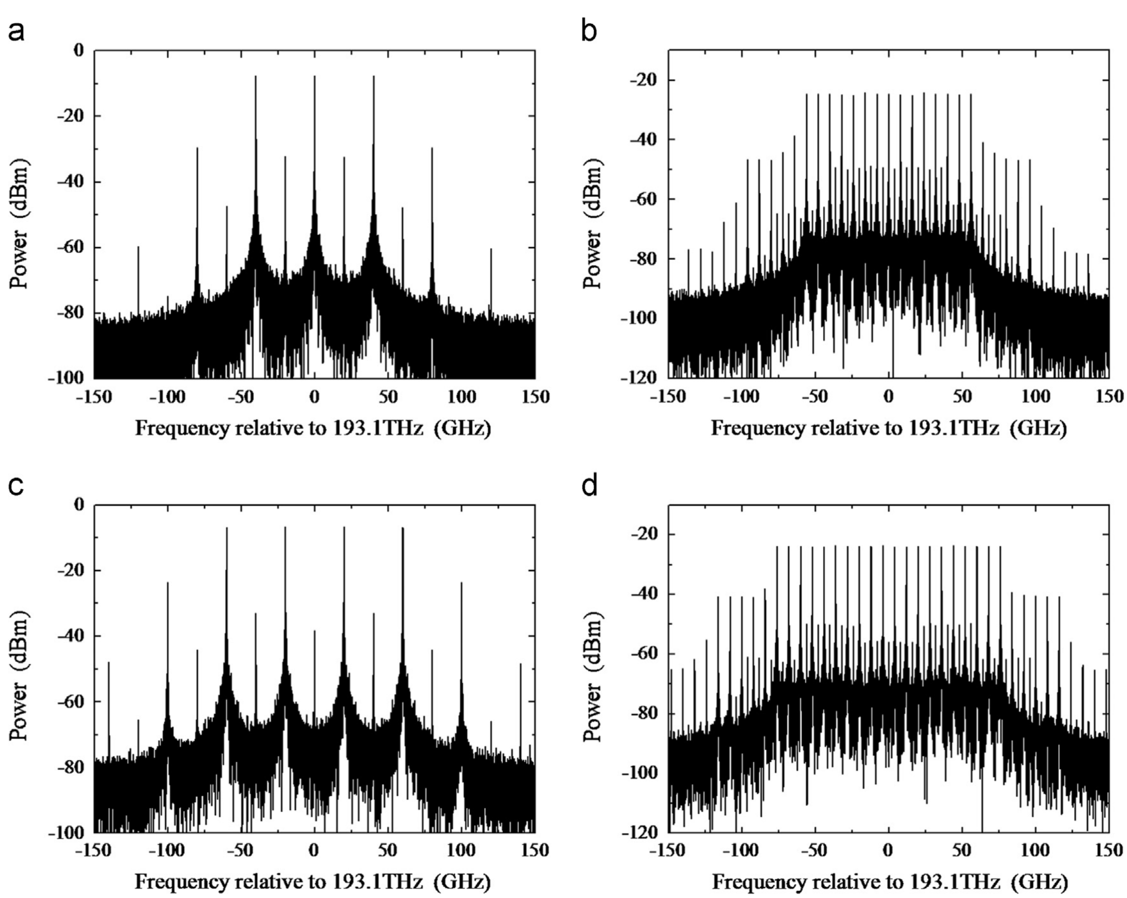

Fig. 2. Simulated output spectrum when IM1 is biased at its maximum transmission: (a) 3-line frequency comb with a spacing of 40 GHz, (b) 15-line frequency comb with a spacing of 8 GHz; simulated output spectrum when IM1 is biased at its minimum transmission: (c) 4-line frequency comb with a spacing of 40 GHz, (d) 20-line frequency comb with a spacing of 8 GHz.