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Simple optical frequency comb generation using a passively mode-locked quantum dot laser

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ABSTRACT

A simple and quasi-tunable optical frequency comb (OFC) generator is proposed and experimentally demonstrated using a C-band passively Fabry-Pérot quantum dot mode-locked laser and a dual-driven $LiNbO_3$ Mach–Zehnder modulator. A 16-nm bandwidth OFC with 81, 58 and 30 comb lines at frequency interval of 23.3 GHz, 35 GHz and 70 GHz respectively is obtained experimentally. Measured average optical signal to noise ratio of 10-dB bandwidth OFCs is 36.3 dB, 38.5 dB and 40.8 dB at frequency interval of 23.3 GHz, 35 GHz and 70 GHz, respectively. Besides, single-sideband phase noise of the 23.3 GHz and 35 GHz frequency comb is −110 dBc/Hz and −102 dBc/Hz at an offset of 1 kHz, respectively. RF linewidth of the 23.3 GHz and 35 GHz OFC is about from 275 Hz to 289 Hz. This is considered a very simple OFC generator with a broadband and seamless spectrum.

1. Introduction

Optical frequency comb (OFC) generator is highly desirable in many applications, which requires flat comb lines, equal frequency interval and tunable wavelength. For example, OFC can be used as a multi-carrier optical source for optical orthogonal frequency division multiplexing systems, the generation of high frequency Millimeter / Terahertz wave in radio over fiber systems and dense wavelength division multiplexed systems [1–3].

Numerous schemes of wideband OFC generation have been demonstrated. One technique is to use a mode-locked laser (MLL) [4,5]. MLL based OFCs are broadband with many comb lines, but they are in lack of controllability of optical frequency interval. In contrast, either high nonlinear fiber (HNLF) or micro-resonator can be used for OFC generation [6–8], leading to a small-size and robust system. The limitations of this technique are that high optical power operation and high quality optical/electrical filter for spectrum shaping are required. In [7], an OFC generator uses HNLF combined with two CW lasers, which obtains an equalized optical comb with 150 nm bandwidth. But very high optical power and strict phase-matching are required. In [8], an HNLF based OFC has 1500 modes over a bandwidth of 120 nm. However, it needs the optical power beyond 50 W prior to HNLF. Another typical scheme of broadband OFC generation is mainly based on electro-optical modulation, which can be found in [9–13]. In [10], a wavelength tuning range is improved to 40 nm, but the comb lines are not simultaneous and seamless. In [12], although an OFC with a bandwidth of 10 nm is obtained using a dual-driven Mach–Zehnder modulator (DD-MZM), feedback loops and high quality optical filters are needed. In [13], another OFC with a discontinuous wavelength range of 50 nm is obtained using an MZM with two accurately synchronized radio frequency (RF) signals driven at the power beyond 35 dBm.

Recently, either a quantum dot laser or quantum cascade laser is used for OFC generation, which is highly integrated, and has wide bandwidth, high repetition frequency and robust stability [14,15]. In [14], an OFC is obtained using a two-section InAs/InP quantum dot mode-locked laser (QD MLL), with a bandwidth of 20 nm and optical linewidth smaller than 100 kHz. In [15], a quantum cascade laser generates 5 mW of terahertz power spread across 70 comb lines. However, there are not enough evidences to confirm the comb lines with low phase noise.

In this paper, we propose and experimentally demonstrate a novel and simple technique to generate OFC using a passively InAs/InP QD MLL with a commercial $LiNbO_3$ DD-MZM driven. Experimentally, we have generated quasi-tunable OFC with frequency intervals of 23.3 GHz, 35 GHz and 70 GHz, which spreads across simultaneous and seamless 86, 56 and 30 comb lines in a 10-dB spectrum

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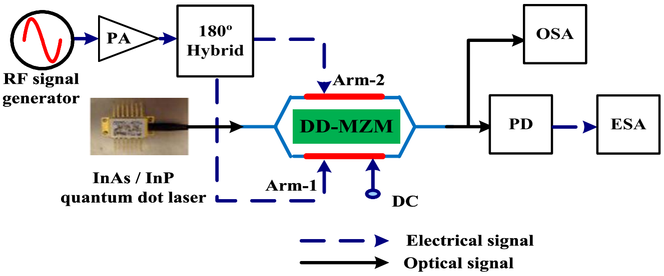

Fig. 1. Schematic diagram of OFC generator using a QD laser. PA: power amplifier; PD: photodetector; ESA: electrical signal analyzer; OSA: optical spectrum analyzer.

bandwidth, respectively. Compared with the reported OFC generators [4–13], this scheme is not using polarization controllers, optical filters and optical phase lock loops, so it is considered very simple. Using this technique, it is easy to generate quasi-tunable and low phase noise OFCs with seamless broadband and high stability.

2. Experimental results and discussion

The schematic configuration of our proposed OFC generation is shown in Fig. 1, consisting of a passively InAs/InP QD MLL, a commercial $LiNbO_3$ DD-MZM (Sumitomo, V_π =5.3 V, with one DC bias), an RF signal generator (Hittite-T2240), and an RF power amplifier. The QD laser that is used has a single section monolithic InAs/InP QD Fabry-Pérot laser cavity with emission in the C-band wavelength range from 1528 nm to 1560 nm (including 57 comb lines). The output spectrum directly from the QD laser has high performance [16,17], such as the optical linewidth of less than 150 kHz, the relative intensity noise (RIN) of less than −154 dB/Hz, the optical signal-to-noise ratio (OSNR) of up to 60 dB, and the RF linewidth of less than 20 kHz, etc. In Fig. 1, a sinusoidal wave RF signal is amplified and divided into two RF components with equal power by an 180° hybrid splitter. Each RF component is fed to each electrode of the DD-MZM (Arm-1 and Arm-2). One bias voltage is used to set the operating point of the DD-MZM. Note that this bias voltage is important to improve the flatness of OFCs. The performance of the OFCs generated is characterized using an optical-complex spectrum analyzer (OSA) (APEX 2443B), an electrical signal analyzer (ESA) (Agilent N9030A PXA), a 50-GHz bandwidth photodetector (PD) (SHF 47100 A) and a power meter (Newport 840).

Basically, to generate a flat OFC with an MZM, an asymmetric drive condition should be applied [18]. Suppose two RF drive signals for two Arms of DD-MZM are $V1(t) = V1 \sin \omega t$ and $V2(t) = V2 \sin \omega t$; θ is the phase of the optical wave in Arm-1 driven by the DC bias voltage; ϕ_0 is a constant phase shift by applying the RF modulation voltage; ϕ_1 and ϕ_2 are the phases induced by the RF modulation voltages in Arm-1 and Arm-2, respectively. According to the modulating characteristics of DD-MZM [18], $\phi_{1,2}$ is given by

$$\phi_{1,2} = \frac{V_{1,2}(t)\pi}{V_\pi}, \tag{1}$$

and the θ is given by

$$\theta = \frac{V_{DC}\pi}{V_\pi}. \tag{2}$$

Where V_{DC} represents the direct current (DC) bias voltage of DD-MZM. Assume $\Delta\phi = \phi_1 - \phi_2$ and $\Delta\theta = \theta_1 - \theta_2$.$\Delta\phi$ represents the phase difference induced between Arm-1 and Arm-2; $\Delta\theta$ represents the phase difference induced by DC bias voltage. Because of a push-pull DD-MZM and avoiding the frequency chirp, this suggests $V_1(t) = -V_2(t)$. To generate a flat OFC, the flat spectrum condition should be satisfied [19].

$$\Delta\phi + \Delta\theta = \pi. \tag{3}$$

According to Eq. (1), the two RF signals are out of phase, i.e.$V1(t) = -V2(t) = V$, then $\Delta\phi = 2\pi V/V_\pi$, and thus a flat OFC can be generated. We also measure and record the transmission characteristics of the DD-MZM, which are depicted in Fig. 2(a)-(b). Fig. 2(a)

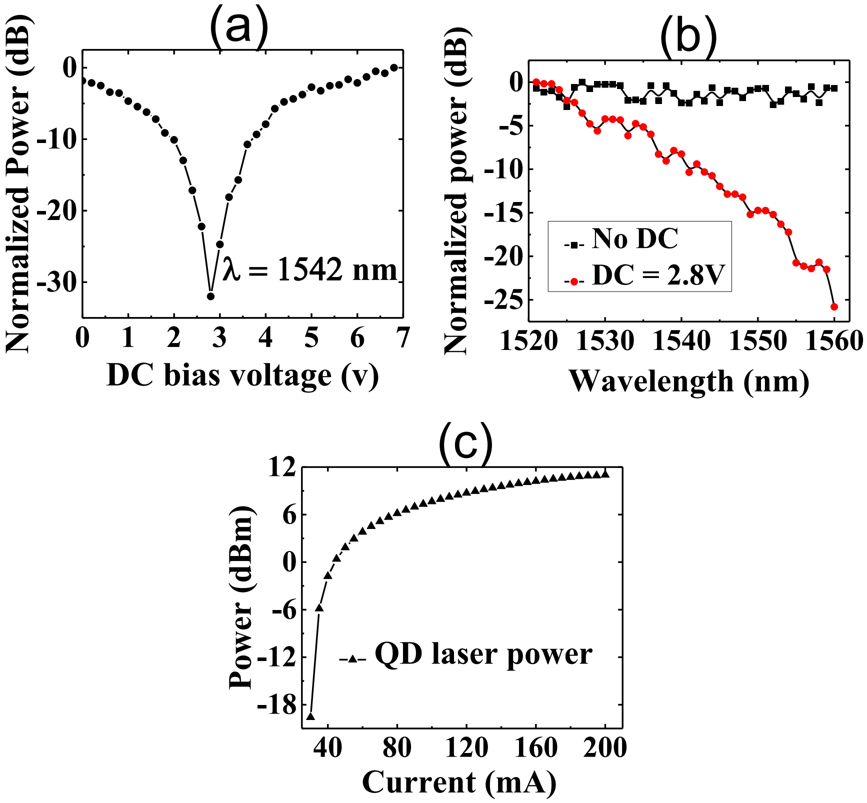

Fig. 2. (a) Single wavelength modulation characteristic of DD-MZM at 1542 nm; (b) multiple wavelengths modulation characteristic of DD-MZM at 0 and 2.8 V bias; and (c) QD laser optical output power versus bias current.