O-band 100 GHz quantum dot mode-locked optical frequency comb with 128 Gbit/s/ λ PAM-4 optical transmission ability

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Abstract: We demonstrate a cost-effective O-band 100 GHz Fourier-transform-limited optical frequency comb with 128 Gbit/s/ λ PAM-4 transmission ability, generated from a specially designed two-section InAs/GaAs quantum dot mode-locked laser.

1. Introduction

The optical frequency comb (OFC), providing a direct connection between optical and microwave domains, have revolutionised numerous fields from metrology to optical communications over the last two decades [1,2]. There are various ways to generate OFC, including gain switching, nonlinear effect, electro-optic modulation, and microresonator systems. Nonetheless, one of the most potent sources of OFC generation is mode-locked lasers (MLLs), who create a pulse train in the time domain and equal-distributed lines in the frequency domain, simultaneously. To date, the MLLs utilising quantum dot (QD) structure as the active region have demonstrated several advantages over their quantum well (QW) counterparts, including the low threshold current, broad gain spectrum, and ultrafast carrier dynamic [3]. And the latest research has proved that the QD-MLL could be a feasible light source in future compact, high-efficiency, and cost-effective optical network systems [4].

Since the first declaration of the ITU-T G.694.1 Recommendation in 2002, the QD-MLLs-based OFC sources with a large mode-spacing (i.e., the repetition rate ≥ 100-GHz) are always desired in the dense wavelength-division multiplexing (DWDM) transmission systems due to their capability of potentially diminishing the number of required light sources. Despite a wide variety of accomplished 100 GHz comb sources via high order harmonics [5] or complicated system-level setup [6], obtaining such large mode-spacing combs by the fundamental repetition rate of a QD-MLL remains a challenge, mainly attributed to the scarcity of high-gain materials needed in extreme-short-cavities. With careful choice of the resonator material and unique design of the laser cavity, here, we use a QD-MLL-based 100 GHz transform-limited OFC source to successfully demonstrate 128 Gbit/s/λ PAM-4 back-to-back (B2B) and 5km SSMF transmission at a symbol rate of 64 Gbaud. The results suggest that our proposed two-section QD-MLL is a promising candidate for easy-operation, cost-effective, and high-efficiency DWDM light source.

2. Device characterisation

The devices presented in this work were prepared via vacuum-based layer-by-layer deposition in a solid-state molecular beam epitaxy (MBE), with emission wavelength in the 1.3 µm range. The self-assembled InAs QD structure was grown on a Si-doped GaAs (001) surface along with AlGaAs cladding layers and highly doped GaAs contact layers. An extraordinary design is employed in the active region to maintain the high QD density (5.9×10^{10} cm^{-2}) while preserving the QDs uniformity. A detailed description of the entire growth procedure can be found in ref.[4]. Then, the passive MLLs with a typical two-section structure were manufactured from the well-prepared wafer following standard etching and metal-dielectric deposition techniques. As depicted in Fig. 1(a), the 5-µm-wide ridge lasers with a determined 405 µm cavity length (aim to realise ~100 GHz fundamental repetition rate) contain a gain-to-absorber length ratio equals 7:1. An electrical isolation resistance of around 2.5 kΩ was achieved by selectively removing a 10-µm-long gap between the gain section and the saturable absorber (SA) section. Then, a high-reflective (HR) coating was applied on the facet close to the SA section while the facet near the gain section was left to as-cleaved. Finally, the devices were mounted p-side up on a heat sink, gold-wire-bonded, and packaged with a TEC controller to fix the heat sink temperature at 20°C. It should be noted that the mode-locking phenomenon was obtained with just the current source; therefore, these two-section MLLs operated as single-section self-mode-locked (SML) lasers since their SA sections were left floating. The typical light-current-voltage (*L-I-V*) curve of the device under investigation is plotted in Fig.1(b), where a 20-mA threshold current and a 17.7% slope efficiency are exhibited. Meanwhile, the small hysteresis loop near the threshold current indicates the bistability of this device.

Figure 2(a) shows the OSA spectrum of the optical combs under bias condition of I_{gain} = 66 mA, which exhibits a centre wavelength of 1290.755 nm with 7 potential channels within a 3-dB bandwidth of 3.46 nm. The inset of Fig.2(a) presents a high-resolution OSA spectrum for four adjacent tones, where a fundamental repetition rate of 94.6 GHz can be evidenced by the mode-spacing of 0.5248 nm. To the best of our knowledge, this is the highest fundamental repetition rate ever achieved by a single QD-MLL in telecom O-band. The measured pulse duration and calculated TBP under driving conditions range from 20 mA to 80 mA are presented in Fig. 2(b). As can be seen, an unusual phenomenon appears where the pulse duration experiences a steady decrease with increasing current. In the meantime, the spectral width expands with increasing current, resulting in a negligible fluctuation of calculated TBP values in the entire range. Consequently, an average TBP value of 0.472 can be obtained, indicating the nearly Fourier-transform-limited nature of the pulses during the whole mode-locking regime.

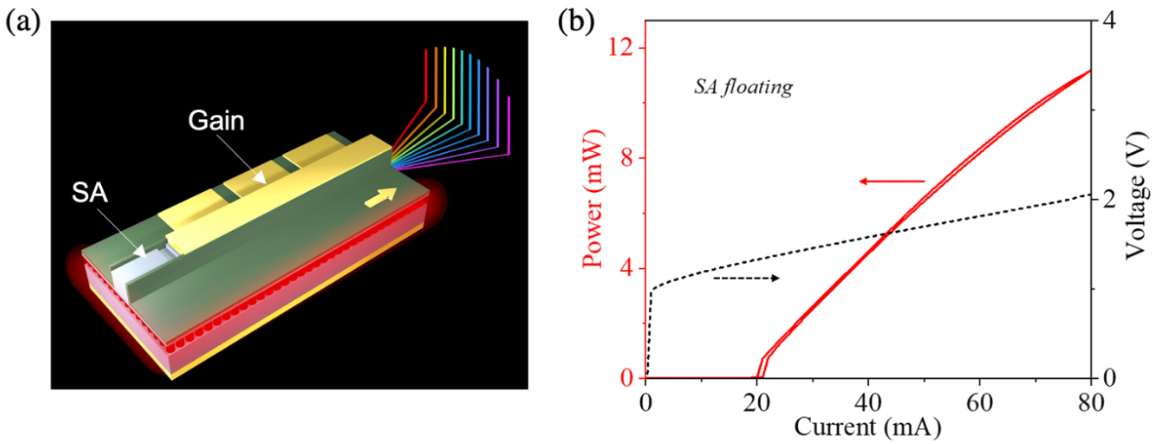

Fig. 1. (a) The schematic configuration of the proposed passive two-section MLL. (b) Room temperature continuous wave *L-I-V* curve with SA floating.

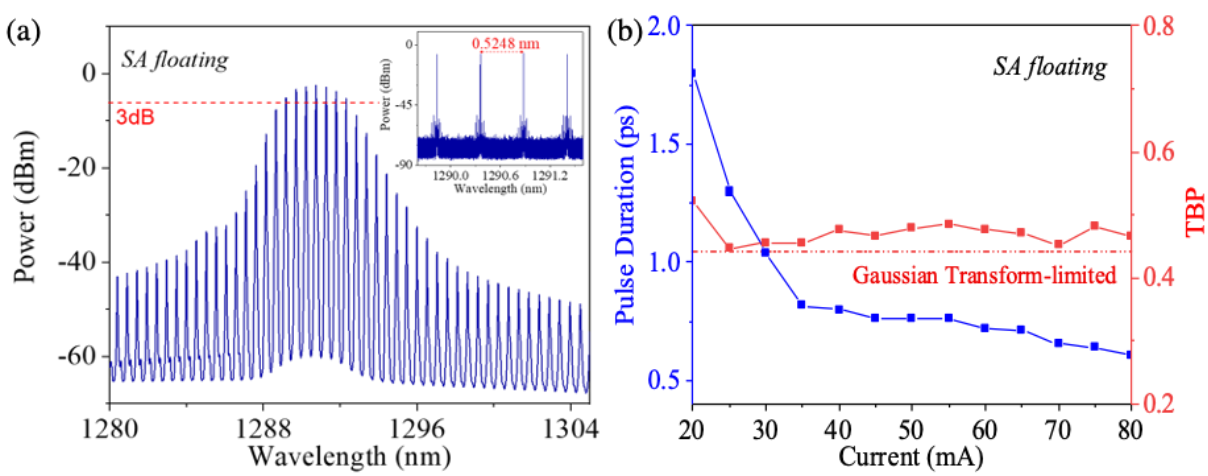

Fig. 2. Room-temperature characteristics of two-section unbiased passively QD MLL with SA floating. (a) OSA spectrum under bias condition of I_{gain} = 66 mA. (Inset: high-resolution optical spectrum for adjacent channels (Resolution: 0.04 pm).) (b) Measured pulse durations and corresponding calculated TBP values in the range of I_{gain} from 20 mA to 80 mA.

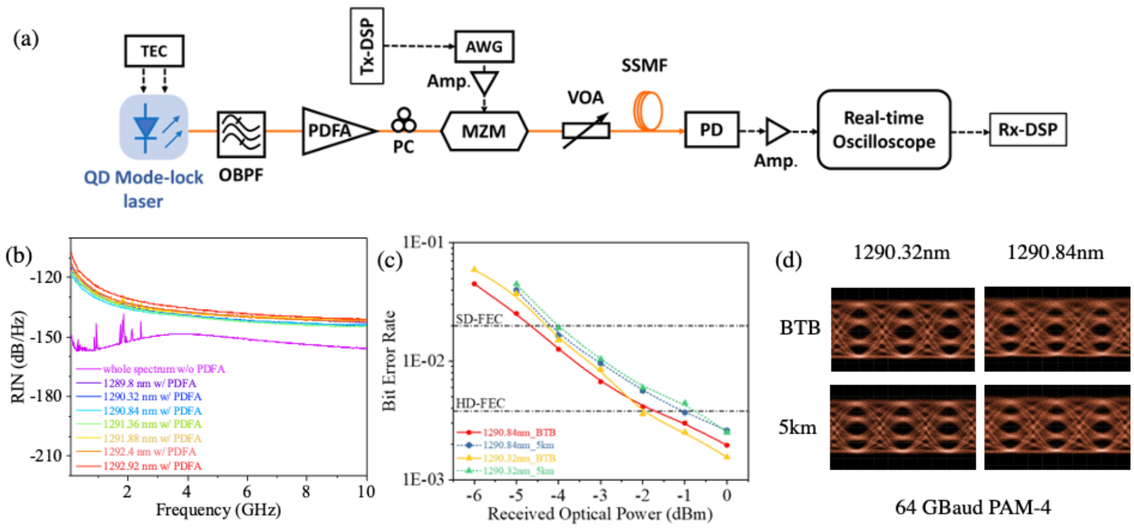

Fig. 3. (a) 64 Gbaud PAM-4 data transmission setups. (b) Room temperature RIN spectra of the whole spectrum and the 7 filtered channels within the 3dB bandwidth under bias condition of I_{gain} = 66 mA. (c) BER versus received optical power for B2B and 5km SSMF transmission using the wavelength at 1290.32 nm and 1290.84 nm. (d) Corresponding eye diagrams.

A system-level WDM experiment using 64 Gbaud PAM-4 (128 Gbit/s) modulation format was carried out to verify our device performance in high-speed communication. The experiment setup is depicted in Fig.3(a), the channels we are interested in will be filtered by an optical tunable bandpass filter (OBPF) and boosted by an O-band optical amplifier (PDFA). Then, the amplified signal will be launched into a 40 GHz lithium niobate Mach-Zehnder modulator (MZM) for data modulation, followed by a variable optical attenuator (VOA) to control the received optical power. Subsequently, offline digital signal processing (DSP) was employed for signal demonstration and bit-error-rate (BER) evaluation. The relative intensity noise (RIN) spectra of the whole spectrum and the 7 filtered tones within the 3 dB bandwidth when I_{gain} = 66 mA is shown in Fig. 3(b). As observed, the typical RIN of the whole spectrum and a single tone are -152 dB/Hz and -137 dB/Hz in the range of 100 MHz to 10 GHz, respectively. Certain channels are chosen for both B2B and 5km SSMF transmission, whose BER curves are plotted in Fig. 3(c). The power penalties for these two channels are about 1.6 dBm. The corresponding eye diagrams for both channels after 128 Gbit/s/ λ B2B and 5km SSMF transmission are displayed in Fig. 3(d), where sufficient eye-opening reveals a good signal quality in the digital domain.

3. Conclusion

To sum up, we have developed an O-band 100 GHz OFC source generated by the fundamental repetition rate of a passively two-section InAs QD-MLL. With optimised QD growth conditions, a high dot density is achieved without scarifying the QD uniformity. The specially designed laser structure allows the nearly Fourier-transform-limited pulses with sub-picosecond pulse durations to be detected throughout the whole test range. Additionally, the device shows excellent RIN performance, which is essential to successfully demonstrate a system-level 128 Gbit/s/ λ PAM-4 B2B and 5km SSMF transmissions. Our results pave the way for utilising a small footprint, low power consumption, and easy operation QD-MLLs as efficient OFC sources in future high-speed optical communications.

4. References

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