100 GHz Amplified Mode-locked Frequency Comb with 80 Gbaud NRZ Transmission Ability Based on Ultra-fast Quantum Dot Technology

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Abstract: We demonstrate a 100 GHz repetition rate mode-locked based OFC source and a high gain SOA based on ultra-fast QD dynamics. High-speed optical NRZ data transmission of >80G baud is achieved with the amplified comb.

1. Introduction

Integrated optical frequency comb (OFC) reveals a promising technology to facilitate massive parallelization in dense wavelength-multiplexing division (DWDM) systems in fiber-optic communication [1]. While lasers based on the mode-locking mechanism with ultra-high repetition rate have become a compact, cost-effective, and energy-efficient comb source, the output power is limited due to the short cavity. Semiconductor optical amplifier (SOA) alleviates the power requirement of the comb and compensate for the loss in communication links to support high levels of integration. Semiconductor quantum dot (QD) is an exciting nanostructure to realize performance improvement for these optoelectronic devices [2], and advance integrated photonics systems for high-speed short-reach transmission.

In this work, we proposed an economical, high-power, low-noise OFC strategy based on ultra-fast QD technology. We developed an OFC source with almost 100 GHz fundamental repetition rate and a high unit gain (13.6 dB/mm) SOA fabricated from the same InAs QD wafer operates at 1.3 μm. The amplified comb light, including static and dynamic properties is examined in detail. We further leverage these two performant devices at a system level to assess the feasibility of high-speed transmissions.

2. Material and device design

The comb source and SOA were developed based on GaAs (001) substrate using molecular beam epitaxy. Fig. 1(a) shows the layer structure of the fabricated ridge waveguide devices. The active region consists of a tenfold self-organized InAs QDs that is p-type modulation doped. The inset in Fig.1 (b) shows the cross-sectional transmission electron microscope (TEM) image of the multi-stacks QD layers. A strong room temperature (RT) photoluminescence (PL) emission is observed with the ground state (GS) having a peak wavelength at 1285.7 nm and full width at half maximum of 42.2 nm, as displayed in Fig. 1(b). All the narrow ridge waveguide devices are fabricated simultaneously through standard semiconductor lithography and etching techniques. Detailed information on the procedures can be found in [3]. Fig.1(c) illustrates the waveguide structure of each device. For the two-section MLL-based OFC source, the ridge width is 5 μm, and the cavity length is 0.4mm (saturate absorber length: 56 nm). The rear facet is coated with 95% high-reflection coating, whereas the front facet is left as-cleaved. For the traveling-wave SOA, the chip length is 1.8 mm, and the ridge width is tapered from 2 μm to 4 μm towards both facets. This tapered waveguide design, together with the 8° tilted angle and 0.3% anti-reflection coating on both facets, is employed to suppress the residual reflection and inhibit lasing. The chips are then butterfly packaged with thermoelectric coolers for stable and portable operation.

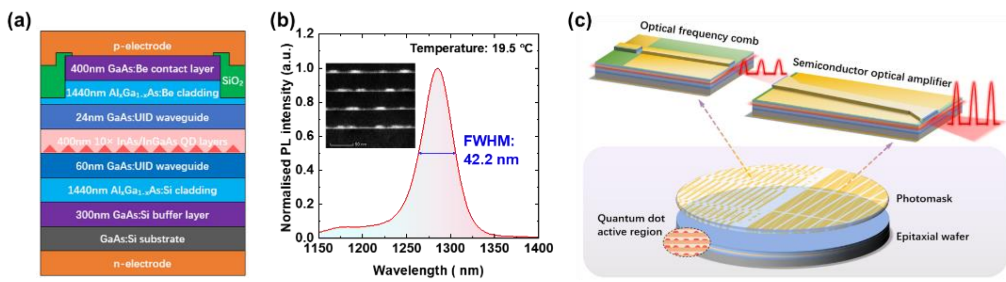

Fig. 1 (a) Layer structure of the ridge waveguide devices. (b) RT PL spectrum of the wafer. (Inset: Cross-sectional TEM image of the QD active layers) (c) Schematics of the device structures.

3. Results and discussions

The measured threshold current of the OFC source is 18 mA, and the slope efficiency is 0.16 W/A, as depicted in Fig. 2 (a). The ultra-short cavity of the OFC source yields a 96 GHz fundamental repetition rate (See inset in Fig.2(a)). No lasing phenomenon is observed for SOA as the current increased to 200 mA. The highest on-chip gain at 1290 nm is 24.5 dB at the current 160 mA (as shown in Fig. 2(b)), corresponding to a gain per length of 13.6 dB/mm. To the best of our knowledge, this is the highest unity gain achieved among all the published QD SOAs operating in O-band. The saturation output power and the fiber-to-fiber noise figure are 10 dBm and 5 dB, respectively.

We then investigated the interaction between the ultra-fast optical pulses and the optical gain spectrum of the QD SOA. Fig. 2(c) shows the lasing spectra consisting of comb lines ranging from 1287 nm to 1295 nm before and after amplification, with 6 channels being preserved in the 3-dB bandwidth. This consistency in the comb's spectral shape is attributed to the perfectly matching emission wavelength originating from the same QD wafer. The fiber-to-fiber gain for each channel fluctuated between 4-4.5 dB. It is found that the gain-per-channel is decreased with increasing the number of comb lines. Three channels within 3-dB bandwidth were then filtered by the optical tunable bandpass filter to maintain a relatively high gain condition. With the inclusion of QD SOA, the modal relative intensity noise (RIN) is reduced in the range of 100 MHz to 5 GHz, as displayed in Fig. 2(d). The practicality of high-speed data communication is then evaluated by the amplified comb channels at the system level. The system setup is almost the same as previously reported [3]. The three amplified filtered channels are used for back-to-back transmission of up to 80 Gbaud non-return-to-zero (NRZ) signals. The corresponding bit error rate (BER) performance is given in Fig. 2(e), where channel 2 shows the lowest BER, and channel 6 presents the worst performance owing to the high RIN level and low output power. BER directly from the comb source is unattainable due to equipment limitations. Nevertheless, the closing optical eye diagrams obtained without amplification indicate erroneous BER in Fig. 2(f). We also showed our QD SOA outperformed the commercial praseodymium-doped fiber amplifier (PDFA), as evidenced in Fig. 2(f).

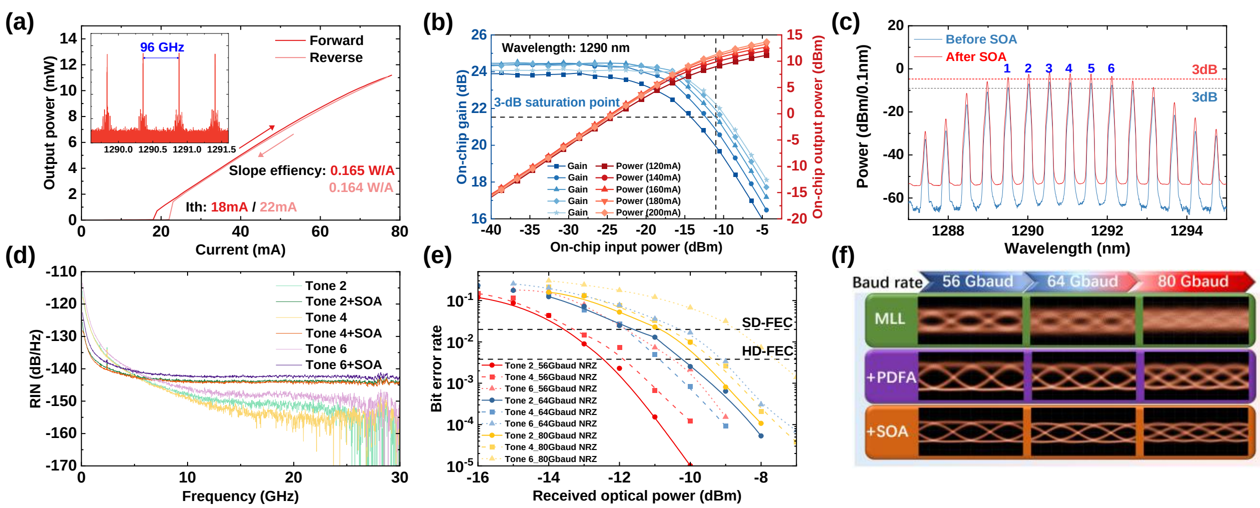

Fig. 2 (a) OFC source light-current characteristic. (Inset: optical spectrum at 66 mA) (b) SOA gain characteristic at 160 mA. (c) Optical spectra of the OFC source before and after amplification. (d) Modal RIN spectra of three filtered channels. (e) Back-to-back BER versus received optical power of the amplified filtered three channels. (f) Optical eye diagrams of channel 2 before and after amplified by QD SOA and PDFA.

4. Conclusion

We have demonstrated the amplification of the OFC source with an ultra-fast repetition rate of 96 GHz using the high gain SOA originating from the same QD wafer. With the inclusion of the QD SOA after the OFC source, uniform amplification of power-per-channel, and suppression in RIN level at low frequencies is presented. The high-speed transmission results of 80 Gbaud NRZ signal achieved with a total chip length of 2.2 mm indicate the high compatibility between OFC and SOA, meanwhile, highlighting the importance of ultra-fast gain dynamics in QDs.

5. References

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