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# Passively mode-locked monolithic two-section gain-guided tapered quantum-dot lasers: II. Record 15 Watt peak power generation

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In recent years, quantum-dot (QD) mode-locked semiconductor lasers have shown great potential as ultrashort pulse laser sources [1]. For instance, the generation of ultrashort transform-limited pulses with pulse durations of 360 fs has been previously demonstrated in tapered index-guided mode-locked quantum-dot lasers without any dispersion compensation - however, peak power reached only 2.25 W, for a typical average power of 15.6 mW [2]. In our recent work, we have shown that output average/peak power and pulse energy can be greatly increased using a tapered (or flared) gain-guided structure [3]. In [3], two-section devices incorporating 5 or 10 QD layers with a total length of  $\sim 2.78$  mm were used, resulting in pulse repetition rates of the order of 14.6 GHz. With an absorber-to-gain lengths ratio of 1:7, the highest peak power achieved was 3.6 W from both QD structures. On the other hand, a maximum average power of 209 mW corresponding to 14.2 pJ pulse energy with 6-ps pulse duration was achieved for the 5-layer QD laser. The generation of high-peak-power pulses is vital for a variety of applications such as biomedical nonlinear microscopy and imaging, where a combination of high peak power and average power (up to the limit tolerable by the bio-sample) are most effective in enhancing the nonlinear effects required. In this paper, we report the highest peak power (to our knowledge) of 15 W directly from a monolithic quantum-dot tapered laser, with sub-picosecond pulse width.

The gain-guided tapered laser was grown on a GaAs substrate by Molecular Beam Epitaxy, incorporating 10 identical layers of InAs quantum dots. The investigated gain guided tapered laser consists of two sections: a straight one and a tapered one (angle of  $2^\circ$ ), to which reverse bias and forward bias are applied, respectively. The lengths of the straight and tapered sections are 800  $\mu\text{m}$  and 3.2 mm respectively, the total cavity length thus corresponding to a repetition rate of 10 GHz. A longer tapered section and higher absorber-to-gain lengths ratio (1:4) were chosen to boost the power and generate shorter pulses. Anti- and high-reflective coatings were deposited on the front/back facets. By adjustment of the driving conditions, the shortest pulse generated, with a pulse width of 820 fs, was observed for a reverse bias of  $-4$  V and an injected current of 1 A (Fig.1a). Simultaneously, a high average power of 123 mW was generated, which is made possible due to the increasing width of the tapered section, resulting in a peak power of 15 W. The optical spectrum was centred at 1259.5 nm with a full-width half-maximum of 5.36 nm, resulting in a time-bandwidth product of 0.83. Noise measurements show that timing jitter can be as low as 3 ps. Figure 1b shows the light-current curves at  $20^\circ\text{C}$  with  $-4$  V on the absorber section. A threshold current of 720 mA with hysteresis loop was observed. Mode-locking was also observed for reverse bias between  $-2$  V and  $-6$  V. The maximum output average power achieved was 260 mW, for a reverse bias of  $-4$  V and current 1.7 A at  $20^\circ\text{C}$ , corresponding to 26 pJ pulse energy with 3 ps pulse duration.

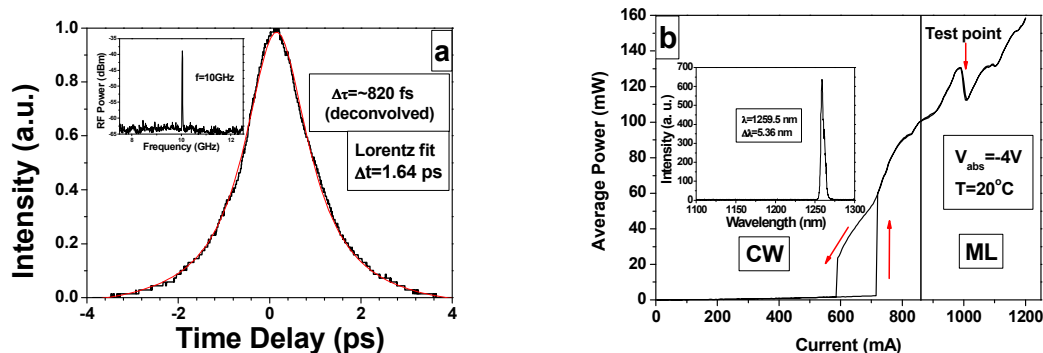


Fig. 1 a) Autocorrelation for an injection current of 1 A and reverse bias  $-4$  V for sub-ps regime; inset: Corresponding RF spectrum b) Light-current characteristic at  $20^\circ\text{C}$  for reverse bias of  $-4$  V inset: Optical spectrum for  $I=1$  A and  $V=-4$  V.

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