High Repetition Frequency Mode-locked Semiconductor Disk Laser

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Abstract: A compact passively mode-locked semiconductor disk laser with a high repetition frequency of 3GHz is demonstrated. 4.9ps pulse duration and 30mW average output power are obtained with 1.4W of 808nm incident pump power. The gain chip consists of 16 compressively strained InGaAs symmetrical step quantum wells in the active region.

1 INTRODUCTION

High repetition frequency pulse trains are suitable for a wide variety of applications, such as optical clocking (Miller, 2000), frequency conversion (Lecomte et al., 2005), high-speed electro-optic sampling (Weingarten et al., 1988), time-resolved spectroscopy (Bartels et al., 1999), and the primary light source for telecommunication systems (Ramaswami and Sivarajan, 1998). For a long time, mode-locked solid-state lasers and edge-emitting semiconductor lasers were the dominators in the field of multi-gigahertz picosecond pulse resources. In recent years, passively mode-locked semiconductor disk lasers (SDLs, also known as optically pumped vertical-external-cavity surface-emitting lasers), have been demonstrated capable to generate multi-gigahertz pulses with high average output power and good beam quality (Hoogland et al., 2000); (Häring et al., 2002); (Aschwanden et al., 2005); (Keller and Tropper, 2006). By comparison, SDLs are cost-effective hence attractive for their potential substitutes of mode-locked solid-state lasers or edge-emitting semiconductor lasers in some applications (Gherman et al., 2004); (Dupriez et al., 2206); (Mihoubi et al., 2008).

After the first report of a passively mode-locked SDL (Hoogland et al., 2000), performance of the mode-locked SDL has been improved significantly: pulse duration to 190fs at 3GHz repetition rate and 5mW output power by a fast SESAM (Klopp et al., 2009); repetition rate to 50GHz with 3.3ps pulse duration and 100mW output power by a low saturation fluence quantum dot SESAM (Lorenser et al., 2006); and average output power to 2.1W at 4GHz repetition rate and 4.7ps pulse duration by the substrate-removing method (Aschwanden et al., 2005). However, the lasing wavelength of a SDL (GaAs based) redshifts at a rate of about 0.3nm/K with increasing temperature because of the intrinsic characteristic of the QWs (Tropper et al., 2004), and this problem has not been solved so far. In this paper, we demonstrate a picosecond passively mode-locked SDL at multi-gigahertz repetition rate. The gain chip is without any post processing (such as substrate-removing and heatspreader-bonding), the fabrication is quite simple and the configuration is compact. Temperature stability of the laser is achieved using the symmetrical step QWs in the active region.

2 EXPERIMENTAL SETUP

Figure 1 shows the gain chip used in the experiments. It contained three main components: the Bragg reflector, the gain region, and the confinement window layer. The Bragg reflector was grown on a GaAs substrate and comprised 27 GaAs/AlAs layer pairs designed to act as a high reflection mirror (calculated reflectivity > 99.95%). The gain region was grown by standard metal-organic chemical vapor deposition (MOCVD) method which consisted of 14 InGaAs quantum

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wells(QW) surrounded by GaAsP barrier layers for a total thickness of 7 λ /2, which allows an efficient absorption of the pump radiation. Finally, a window layer of AlAs was grown and the full structure was completed by a thin InGaP capping layer (not appeared in fig.1). The AlAs window layer prevented the excited carriers escaping to the surface. This surface barrier layer was transparent for the pump wavelength.

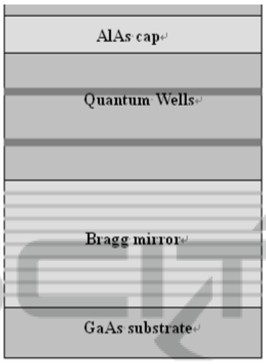

Figure 1: The scheme of the gain structure.

The passively mode-locked SDL with the V-shaped cavity setup is shown in Fig. 2. A 2mm×2mm unprocessed gain chip cleaved off the wafer is directly mounted to a copper heat sink and is temperature controlled by a Peltier cooler. The back plate of the entire device is water-cooled. A fiber-coupled 808nm pump radiation is collimated and focused on the semiconductor disk at an angle of about 45 degree, and the diameter of the pump spot is approximately 100μm. The gain chip is used as a folding mirror, and the laser cavity is ended by a low-temperature grown SESAM and a highly reflective plane-concave output coupler (OC). The folded angle of the cavity is smaller than 10^{o} to reduce the astigmatism.

The curved OC determines a small mode area on the SESAM, such that the saturation energy of the absorber is lower than the saturation energy of the gain medium, as required for pulse formation (Paschotta et al., 2002). In the experiment, the total cavity length is approximately same as the radius of curvature of the OC to force the laser to operate at the edge of the stable region. The lengths of OC arm and SESAM arm are about nine tenths and one tenth of the total cavity length, respectively, to produce a laser spot about 100μm on the gain chip for matching the pump spot. The ratio of the area between the spot on the gain chip and on the SESAM is about 25. With a fixed optimum laser spot on the gain chip, we adjust the lengths of the SESAM arm and the OC arm to obtain a stable continuous-wave (CW) mode-locking operation.

We use an Infiniium 54833A oscilloscope (Agilent Technologies) to monitor the mode-locked pulse trains. The output beam is sent to a FR-103XL autocorrelator (Femtochrome Research) to obtain the autocorrelation trace. Meanwhile, a fast 818-BB-35F InGaAs PIN photoelectric detector (Newport) with 10GHz bandwidth and <35ps rise time and a 40GHz E4447A spectrum analyzer (Agilent Technologies) are used to receive the optical pulses and obtain the radio-frequency (RF) spectrum.

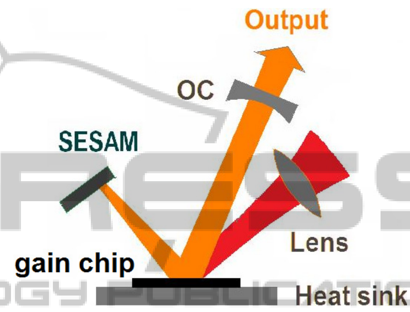

Figure 2: Cavity setup used for the passively mode-locked SDL.

3 RESULTS AND DISCUSSIONS

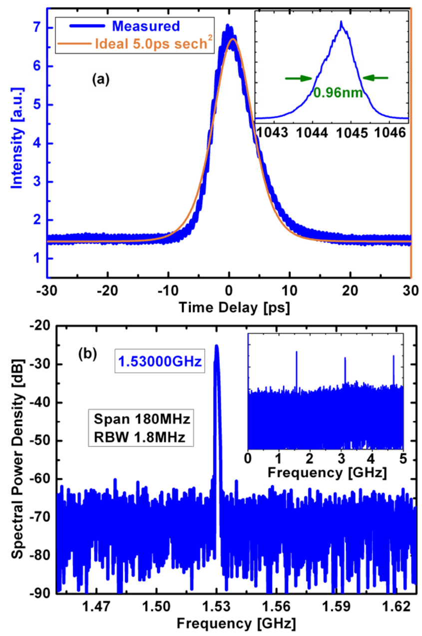

Figure 3: Measured and $sech^2$ fitted autocorrelation trace (a) and RF spectrum (b) of the mode-locked pulses. The inset in (a) shows the optical spectrum and the inset in (b) shows the RF spectrum on a 5GHz span. The radius of curvature of the OC is 100mm.

Firstly, a plane-concave mirror with a radius of curvature of 100mm is used as the OC. The measured and sech^2 fitted autocorrelation trace of the mode-locked pulse trains are shown in Fig. 3(a). The sech^2 fit indicates that the ideal width (full width at half maximum, FWHM) of the pulses is 5.0ps, which is about 4.2 times of the Fourier transform limited sech^2 pulse duration of 1.2ps, according to the inserted optical spectrum with 0.96 nm width. It is known that for a passively mode-locked SDL, the presence of chirp in the pulses is inevitable because of the saturation effect (also known as phase modulation effect) of the gain medium and the SESAM. With some dispersion-controlled elements such as an etalon, the above phase modulation effect can be counteracted and the transform limited pulse trains can be produced (Aschwanden et al., 2005).

Fig. 3(b) shows the RF spectrum of the laser. The frequency span is 180MHz and the resolution bandwidth (RBW) is 1.8MHz. The inset shows the frequency spectrum on a 5GHz span. As shown in Fig. 3(b), the fundamental frequency is 1.5GHz, corresponding to the round-trip repetition rate of 100mm cavity. The RF spectrum trace is free from sidebands down to the level of -35dBc, demonstrating that the SDL exhibits stable CW mode-locking with no Q-switching instabilities.

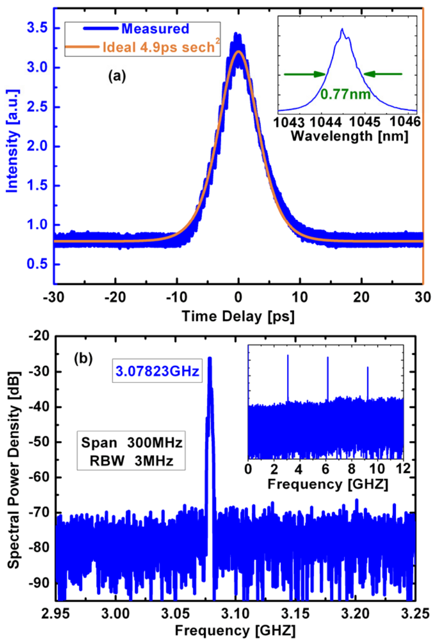

Figure 4: Measured and sech^2 fitted autocorrelation trace (a) and RF spectrum (b) of the mode-locked pulses. The inset in (a) shows the optical spectrum and the inset in (b) shows the RF spectrum on a 12GHz span. The radius of curvature of the OC is 50mm.

When the 100mm radius of curvature of OC is replaced by a 50mm radius of curvature OC, the autocorrelation trace and the RF spectrum of the mode-locked laser are shown in Fig. 4(a) and (b). It can be seen from Fig. 4(a) that the sech^2 fitted pulse duration is 4.9ps, which is about 2.3 times of the Fourier transform limited sech^2 pulse width of 2.1ps, according to the inserted 0.77nm width optical spectrum. Fig. 4(b) shows a 3GHz RF of the mode-locked pulses, and this is consistent with the round-trip repetition rate of 50mm cavity. The RF spectrum trace is free from sidebands down to the level of -45dBc, again demonstrating no Q-switching instabilities in the CW mode-locked SDL.

Figure 5 shows the average output power versus pump power under 3^{o}C heat sink temperature. The repetition is 3GHz, and the laser operates in a circular TEM_{00} mode. The maximum average output power of 30mW is reached with 1.4W pump power; the slope efficiency (SE) and the optical-to-optical conversion efficiency are about 3.1% and 2%, respectively. Limitations of the output power and SE are mainly result from the thermal problem. We soldered the gain chip to a heat-spreader to remove the thermal and then the output laser could be higher.

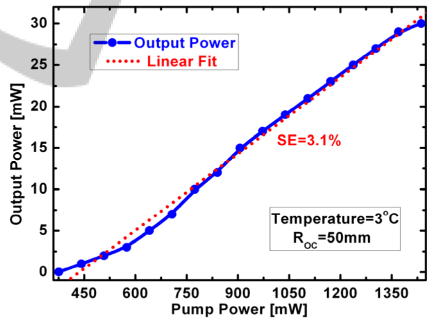

Figure 5: Average output power of the mode-locked laser at 3GHz repetition rate versus pump power at a temperature of 3^{o}C.

4 CONCLUSIONS

We have demonstrated a compact passively mode-locked SDL. The CW mode- locking operation at 3GHz repetition rate, 4.9ps pulse duration and 30mW average output power are obtained using a low-temperature grown SESAM. The laser can be used as gigahertz picosecond pulse source in many applications.

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