Chapter 3

Quantum-Well Semiconductor Saturable Absorber Mirror

The shallow modulation depth of quantum-dot saturable absorber is unfavorable to increasing pulse energy and peak power of Q-switched laser. It is still need another approach for passively Q-switching at 1.3 μm. So that we demonstrate the first use of InGaAsP quantum wells as a saturable absorber in the Q-switching of a diode-pumped Nd-doped 1.3-μm laser. The barrier layers of this InGaAsP device are designed to be a strong absorber for the suppression of the transition channel at 1.06 μm. With an incident pump power of 1.8 W, an average output power of 160 mW with a Q-switched pulse width of 19 ns at a pulse repetition rate of 38 kHz was obtained. Compare to quantum-dot saturable absorber it substantially increase the modulation depth for passively Q-switching at 1.3 μm. Then, we'll introduce semiconductor saturable absorber based on InGaAs/GaAs quantum wells that have been successfully developed for mode-locking or Q-switching of diode-pumped Nd-doped lasers operating around 1.06 to 1.3 μm. This chapter starts from the use of quantum-well materials recently.

3.1 Semiconductor Material

We have talk about QWs structure in SESAMs in last chapter (Ch. 2.1 – 2.2). But the most important factor that decides wavelength and affects other parameters is material. SESAMs for long wavelength (1.3 to 1.5 μm) and high-power short-pulse generation are technologies which people are devoting to develop nowadays. In this thesis, we discuss five materials among most popular optoelectronic semiconductor materials in recent years: InGaAs/GaAs, InGaAsN/GaAs, InAs/GaAs, InGaAsP/InP, and AlGaInAs/InP.

Compact, rugged, all-solid-state Q-switched lasers at 1.3-μm wavelength are of practical importance for numerous applications such as medical diagnostic, fiber sensing, distance measurements, intracavity optical parametric oscillator, and intracavity Raman conversion. Compared with active Q-switching, passive Q-switching is compact and simplicity in operation because it requires no electro-optic or acoustic-optic devices. Nowadays, the saturable absorbers for 1.3-μm lasers comprise V^{3+}:YAG [1-3], Co^{2+}:$MgAl_2O_4$ [4], Co^{2+}:MAS [5], PbS-doped glasses [6], and semiconductor saturable absorber mirrors (SESAMs) [7-10]. The material for SESAMs at 1.3-μm wavelength include InGaAs/GaAs quantum wells (QWs) [7], GaInNAs/GaAs QWs [3.8,3.9], InAs/GaAs quantum dots (QDs) [10], and InGaAsP/InP bulk layers [11]. InGaAs QWs for 1.3-μm SESAMs have the drawback of large insertion losses because the high indium concentration gives rise to significantly strained layers on the GaAs distributed Bragg reflectors (DBRs). Even though InAs QDs for 1.3-μm SESAMs have lower nonsaturable losses, it is difficult to scale up the amount of the maximum reflectivity change between low and high intensities [10]. On the contrary, the lattice-matched InGaAsP-based SESAMs could offer saturable absorbers with larger modulation depths and longer recovery lifetimes for passive Q-switching operation at 1.3 μm. However, the overall performance of the DBRs on InP substrates are hindered by the disadvantage of small contrast of refractive indices. Even though AlGaAsSb/InP has been demonstrated to be lattice-matched DBRs at 1.55 μm [12], it is more difficult for the 1.3 μm wavelength because the choice of DBR becomes tighter. Nevertheless, the DBRs are merely an optional structure for the cavity design of the passive Q-switched lasers. Without the use of DBRs, the semiconductor saturable absorber (SESA) has to be grown on a transparent substrate. The Fe-doped InP material is a particularly useful substrate to grow the SESA for passively Q-switched Nd-doped or Yb-doped solid-state lasers [13], since it is transparent at the lasing spectral region. More importantly, the double-pass configuration with an external output coupler is beneficial to the flexibility of the cavity design and the optimization of the output coupler.

3.2 InGaAsP QW SESA for Diode-pumped Passively Q-switched 1.34-μm Lasers

Here we present an InGaAsP QW/barrier structure grown on an Fe-doped InP substrate to be a semiconductor saturable absorber (SESA) for a Nd:YVO_4 1.34-μm laser. The novelty of this work lies in the present semiconductor device to serve simultaneously as a saturable absorber for 1.34-μm lasers and a strong absorber for the suppression of the transition channel at 1.06 μm. With an incident pump power of 1.8 W, an average output power of 160 mW with a peak power of 220 W at a pulse repetition rate of 38 kHz was obtained.

3.2.1 InGaAsP QW/barrier structure on Fe-doped InP substrate

This InGaAsP QW/barrier structure was monolithically grown on an Fe-doped InP substrate by metalorganic chemical-vapor deposition. The saturable-absorber region consists of fifteen InGaAsP QWs with the band-gap wavelength around 1.34 μm, spaced at quarter-wavelength intervals by InGaAsP barrier layers with the band-gap wavelength around 1.06 μm. In other words, the composition of the barrier layers was designed to have a strong absorbance at 1.06 μm. With this SESA, the cavity mirrors require no special dichroic coatings to suppress the strongest transition channel at 1.06 μm. The backside of the substrate was mechanically polished after growth. The both sides of the SESA were antireflection (AR) coated to reduce back reflections and the couple-cavity effects. Figure 3.1 shows the transmittance spectrum at room temperature for the AR-coated InGaAsP/InP saturable absorber. The transmittance of the AR-coated Fe-doped InP substrate is also shown for comparison. It can be seen that the strong absorption of the barrier layers leads to a low transmittance near 1.06 μm. On the other hand, an abrupt change in the transmittance near 1.36 μm comes from the absorption of the InGaAsP QWs. The modulation depth of the SESA device is experimentally estimated to be approximately 10 %. The saturation intensities estimated to be in the range of 10 μJ/cm^2.

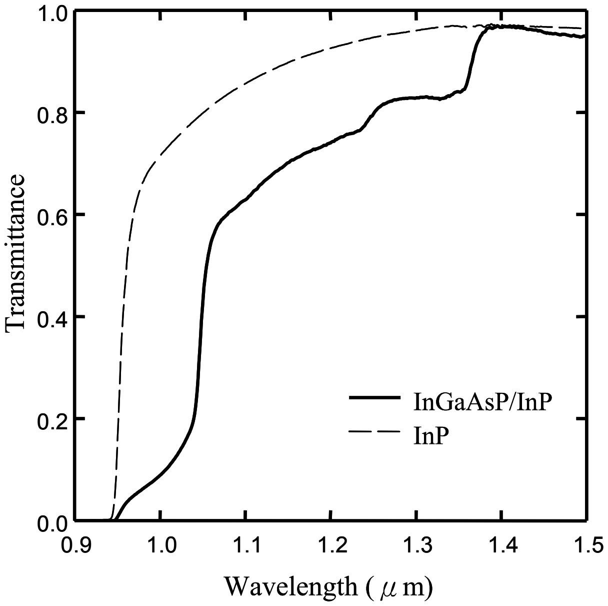

Fig. 3.1. Solid line: the transmittance spectrum at room temperature for the AR-coated InGaAsP/InP saturable absorber. Dashed line: the transmittance of the AR-coated Fe-doped InP substrate.

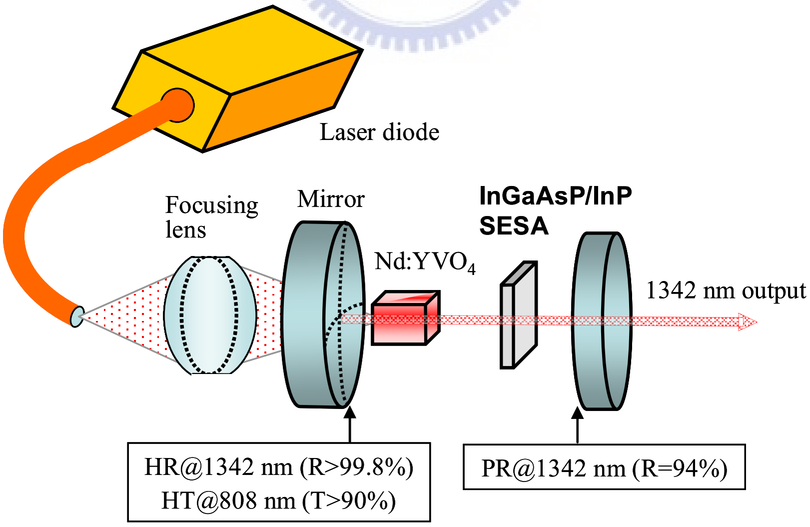

Fig. 3.2. Experimental configuration for the passively Q-switched 1.34-μm Nd:YVO$_4$ laser by use of InGaAsP/InP QWs as a saturable absorber.

3.2.2 Setup and Experiment Result

Figure 3.2 depicts the experimental configuration for the passively Q-switched 1.34 μm Nd:YVO_4 laser by use of InGaAsP/InP QWs as a saturable absorber. The active medium was a 0.5 at.% Nd^{3+} , 6-mm-long Nd:YVO_4 crystal. Both sides of the laser crystal were coated for antireflection at 1.34 μm ($R<0.2\%$). The pump source was a 2.0-W 808-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.16. Focusing lens with 16.5 mm focal length and 90% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius was around 100 μm. The input mirror was a 500 mm radius-of-curvature concave mirror with antireflection coating at the diode wavelength on the entrance face ($R<0.2\%$), high-reflection coating at lasing wavelength ($R>99.8\%$) and high-transmission coating at the diode wavelength on the other surface ($T>90\%$). Note that the laser crystal was placed near the input mirror (<1 mm) for the spatial overlap of the transverse mode structure and radial pump power distribution. The reflectivity of the output coupler is 94% at 1342 nm. The overall Nd:YVO_4 laser cavity length was approximately 20 mm.

Figure 3.3 shows the average output powers at 1342 nm with respect to the incident pump power in cw and passively Q-switching operations. Without the SESA in the cavity, the cw laser at 1342 nm had a slope efficiency of 37% and an output power of 580 mW at an incident pump power of 1.8 W. In the passively Q-switching regime an average output power of 160 mW was obtained at an incident pump power of 1.8 W. The Q-switching efficiency (ratio of the Q-switched output power to the cw power at the maximum pump power) was found to be 27.6%. This Q-switching efficiency is considerably higher than that obtained with InGaAsP SESAM [4] and is close to the results obtained with V^{3+}:YAG [1-3] and Co^{2+}:MAS [5] saturable absorbers.

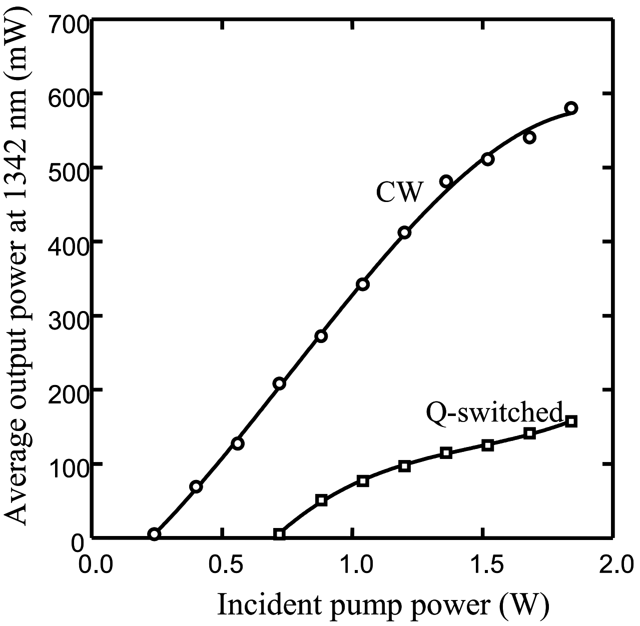

Fig. 3.3. Average output powers at 1.34 μm with respect to the incident pump power in cw and passively Q-switching operations.

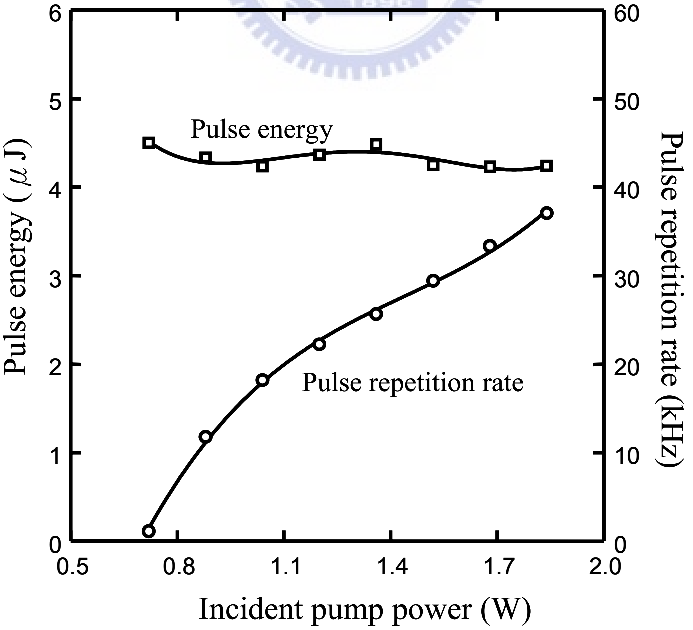

Fig. 3.4. Experimental results for pulse repetition rate and the pulse width versus incident pump power.

The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 G-samples/sec, 1 GHz bandwidth) with a fast p-i-n photodiode. Figure 3.4 shows the pulse repetition rate and the pulse energy versus the incident pump power. The pulse repetition rate increases monotonically with the pump power up to 38 kHz. On the other hand, the pulse energy, like typical passively Q-switched lasers, is insensitive to the pump power. A typical oscilloscope trace of a train of output pulses and an expanded shape of a single pulse are shown in Fig. 3.5. Under the optimum alignment condition, the pulse-to-pulse amplitude fluctuation was found to be within ±5%. The pulse width was measured to be 19 ns. As a consequence, the peak power was found to be higher than 220 W.

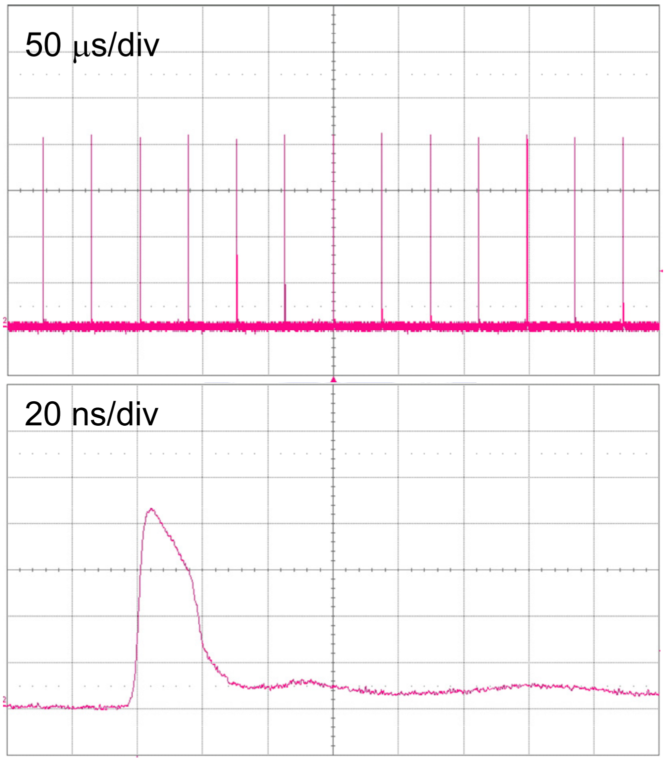

Fig. 3.5. (a) typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

3.2.3 Conclusion

The InGaAsP QW/barrier structure grown on a Fe-doped substrate was used to be a saturable absorber for the Q switching of a diode-pumped Nd:YVO$_4$ laser operating at 1342 nm. An average output power of 160 mW was obtained at an incident pump power of 1.8W. Stable Q-switched pulses of 19 ns duration with a repetition rate of 38 kHz were generated. The present result indicates the possibility of using InGaAsP QW/barrier structure to generate a Q-switched 1.3-μm laser with the peak power greater than 1 kW.

3.3 InGaAs QW SESAM for Passively Pulsed Nd-doped Laser

InGaAs QWs for >1.3-μm SESAMs have the drawback of large insertion losses, so we were interested in developeing InGaAsP-based SESA. But around 1.1 μm, InGaAs QWs were quite useful. InGaAs QW SESAM for PQS and CML 1.06-μm Nd:YVO_4 laser had been developed in laboratories few years ago. We won't report this part which is relatively mature here. Recently a low-loss SESA based on InGaAs quantum wells is being developed for highly efficient Q switching of a diode-pumped Nd:YAG laser operating at 1123 nm [J11].

Nd:YAG crystals that have excellent optical and mechanical properties have been identified to be one of the promising gain media in diode-pumped solid-state lasers [14–16]. Most of the research involving the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd:YAG crystals were focused on the wavelength of 1064 nm. However, there are many Stark components in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of the Nd:YAG crystal, such as 1112, 1117, and 1123 nm [14]. Even though the fluorescent intensity at 1123 nm is in excess of ten times smaller than that at 1064 nm, the diode-end-pumped configuration has been successfully used to achieve highly efficient Nd:YAG 1123 nm lasers [17–21]. The 1123 nm laser has been demonstrated to be a useful pump source for a thulium upconversion fiber laser with blue light emission [17,22]. Recently, a diode-pumped passively Q-switched Nd:YAG 1123 nm laser has been achieved by the use of a Cr^{4+}:YAG crystal with a low modulation depth as a saturable absorber [20]. Note that the modulation depth is defined as the maximum change of absorption (or reflectivity), which can be induced by incident light with a given wavelength. Nevertheless, the nonsaturable losses of the Cr^{4+}:YAG crystal are relatively high in comparison with the gain of the Nd:YAG crystal at 1123 nm. As a consequence, the Cr^{4+}:YAG crystal brings about a considerably low Q-switching efficiency (ratio of the Q-switched average output power to the cw output power at the same pump power) in the Nd:YAG 1123 nm laser. Therefore it is of practical value to develop the saturable absorbers with low modulation depths (<5%) as well as low nonsaturable losses for the low-gain Nd:YAG 1123 nm laser.

InGaAs/GaAs QWs have often been used as SESAMs in Nd-doped lasers at 1.06 μm [23]. Even so, such highly strained QWs were previously difficult to use as saturable absorbers for the wavelengths beyond 1.1 μm because of their high nonsaturable losses [24]. Recent progress in the growth methodology has made it possible to realize InGaAs QWs with emission wavelengths up to and somewhat beyond 1.2 µm [25–27]. However, to our knowledge, there has been no work using InGaAs QWs to be SESAMs in Nd:YAG lasers at 1123 nm. Here, for what is believed to be the first time, a diode-pumped passively Q-switched 1123 nm Nd:YAG laser with InGaAs QWs as a saturable absorber is achieved. With an incident pump power of 16 W, the compact laser cavity produces an average output power of 3.1 W at 1123 nm with a repetition rate of 100 kHz and a pulse width of 77 ns. The extremely low nonsaturable losses of the SESAM lead to the Q-switching efficiency to be up to 94%.

3.4 Conclusion and Future Work

We reported our work on InGaAsP/InP QWs SESA and InGaAs/GaAs QWs SESAM for PQS DPSSL. Compare to InAs/GaAs QD saturable absorber, the first use of InGaAsP/InP QW saturable absorber successfully improved output performance in the Q-switching of a diode-pumped Nd-doped 1.3-µm laser. Almost 10 times the pulse energy and 44 times the peak power under even lower pumping power were showed in Table. 3.1. Attempts to use InGaAsP-based SESA to scale up Nd-doped 1.3-µm lasers are under way.

Table 3.1. Comparison between InAs/GaAs QD SESAM and InGaAsP/InP QW SESA for PQS output performance (from Ch 2.4 and Ch 3.2)

PQS DPSSL with…	InAs/GaAs QD	InGaAsP/InP QW	
Pump P_{ave} @0.81µm	2.2 W	1.8 W	
Output P_{ave} @1.34µm	360 mW	160 mW	
Repetition Rate	770 kHz	38 kHz	
Pulse Energy	0.47 µJ	4.2 µJ	
Pulse Width	90 ns	19 ns	
Output P_{peak}	5.2 W	221 W	

InGaAs QWs have been used to be a low-loss semiconductor saturable-absorber output coupler for PQS of a diode-pumped Nd:YAG laser operating at 1123 nm. An average output power of 3.1 W with a Q-switching efficiency of 94% was obtained at an incident pump power of 16 W. Stable Q-switched pulses of 77 ns duration with a repetition rate of 100 kHz were generated. The present result indicates the possibility of using an InGaAs QW structure to mode lock a Nd:YAG laser at 1123 nm. Furthermore, the low-loss SESAM may be employed to generate the high-peak-power yellow laser at 561 nm with intracavity second-harmonic generation.

There is still problem on CML laser at 1.06-1.34 μm by use of QW / QD SESAM. Besides water-vapor absorption [7], the reasons for holes in lasing spectrum of CML laser might be etlon effect and something we do not know yet. The bumpy spectrum could affect the effective spectrum width and pulses.

In addition to developing new materials and band-gap engineering for PQS and CML laser at expanding lasing wavelength, we reported semiconductor QWs as the gain medium of optical-pumped solid-state lasers in next chapter. The motion of electron and hole in transverse dimensions that is typically “not confined” will bring some phenomena also introduced in Ch. 4.4.