

Chapter 2

Quantum-Dot

Semiconductor Saturable Absorber Mirror

We report that a low-loss semiconductor saturable absorber based on InAs/GaAs for applications on PQS, QML and CML lasers. Let's firstly understand the important device, SESAM, before we demonstrate the first diode-pumped PQS and CML Nd-doped laser near 1.3 μm by use of InAs/GaAs QD built up during whole 2004.

2.1 Semiconductor Saturable Absorber Mirror

SESAM is a semiconductor device acting as the mirror and the saturable absorber simultaneously [22,23]. Typically, it contains a Bragg mirror and an absorber layer of QW or QD structure. Such type of SESAMs are also called saturable Bragg reflectors (SBRs), or sometimes simply saturable absorber mirrors (SAMs). A thicker or multiple absorber layers can be used for obtaining a larger modulation depth which means larger capacity of energy storing.

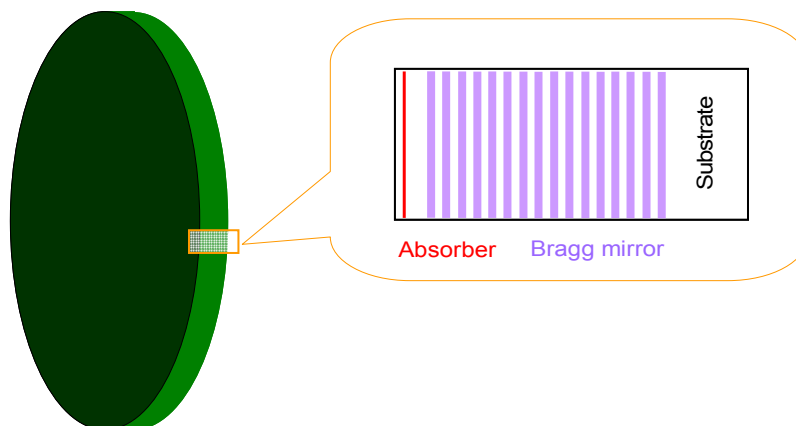


Fig. 2.1. A typical SESAM grown on a wafer of substrate

Periodic structure has applied for spectral confinement in countless devices including SESAM. Distributed feedback laser of side-emission semiconductor laser, fiber Bragg grating of fiber laser, periodically poled lithium niobate as a nonlinear crystal in optical parametric oscillators, and distributed Bragg reflector (DBR) in SESAM were common devices. DBR consists of a sequence of pairs of semiconductor layers with different refractive index. The thickness of each layer is quarter-wavelength of the center wavelength designed for reflection. Utilizing larger difference of refractive index or growing more pairs both can increase the reflectance. However, the difficulty on fabrication and reliability also rise from both methods. So, not all optoelectronics materials used today have corresponding DBR in required wavelength range.

2.1.1 Mechanism of Semiconductor Saturable Absorber

Simply speaking, the saturation of the absorption of a saturable absorber results from the fact that electrons are accumulated in the excited state, then the absorber will not absorb photon anymore while final states are completely occupied. For semiconductor, the saturation results from the fact that carriers are accumulated in the conduction band. The function of saturable absorber is Q-switching, controlling the amount of cavity loss. While the absorber is getting saturate or bleaching, the cavity loss will be decreased to a status of high-Q (low loss). The laser starts building up while the loss below the gain of laser emission, so that the relative life time of excited state, crosssection, and cavity mode size between the saturable absorber and gain medium are essential parameters [24,25].

The properties of a SESA or a SESAM can be uncovered from the measurements of initial transmission by monochromator, modulation depth (ΔR) by Z-scan [26,27], life time and crosssection by temporal analysis from Z-scan, and PL spectrum. For optimization and improvement, more effective and accurate parameters of SESAM (e.g. the spacing control of multiple absorption layers) must be known only after the laser lases.

2.1.2 Influence of Thickness

The influence of thickness is talking about not only the thickness of absorption layer or DBR, but also the depth of cap layer, barrier, and substrate. Resonant and anti-resonant design [9] decide how strong the electro-field inside the SESAM. First the absorption layer was ignored. The thickness of cap layers was set to be 0.5λ and 0.75λ , where λ is the wavelength of lasing. The simulation result in Fig. 2.2

illustrates that smaller electro-field was allowed into the SESAM and less absorption for anti-resonant design. It also means that the resonant design has lower reflectance than anti-resonant design.

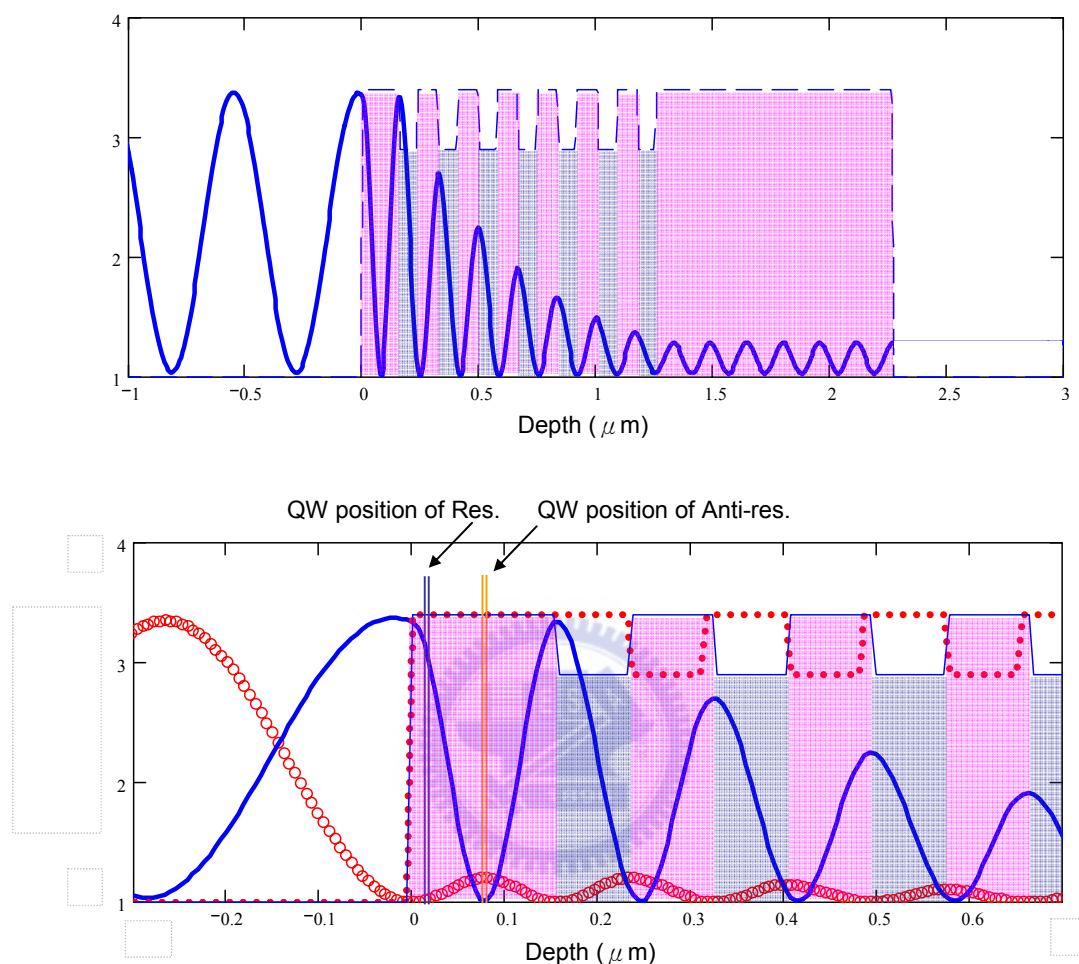


Fig. 2.2. Simulation of incident wave intensity in a SESAM with 7-pair DBR... (Up): resonant design, electromagnetic field (thick line) resonantly transmits into SESAM (dash line). (Down): zoom in the resonant design (blue line) and anti-resonant design (red circle), fewer field transmitted into SESAM that decrease the modulation depth. For both two designs, positions of absorption layers are usually located for high field.

If more absorption is required, multiple quantum wells (MQWs) with half- or quarter-wavelength spacing can be used, especially in SESA (SESAM without DBR). Without fixed node by DBR, wave function with lower threshold corresponding to MQWs with quarter-wavelength spacing in SESA would be lased first.

Thickness of substrate may affect lasing spectral width and further mode-locked pulse width in addition to etalon effect which appears on reflection spectrum. Although anti-reflection coating can reduce influence of substrate, the anti-reflection coating can not be perfect, and its reflectance even can not be as low as coating on crystal.

2.2 Quantum-Well and Quantum-Dot Structure

Just like one-dimension particle in box problem in quantum mechanics, QW structure makes splitting of energy level and provide tunable confinement. A semiconductor QW has effects on the density of states (DOS) for the confined electrons and holes. It can confine electrons in the dimension perpendicular to the deposited layers, while the motion in other dimensions is typically “not confined”.

A QD can be fabricated from a thin layer of semiconductor material embedded in another lattice-mismatched semiconductor material. It is a self-organized tiny structure which can confine electrons in all three dimensions. And the energy levels can be adjusted by controlling the size of QD.

The DOS for bulk (3D), quantum well (2D), quantum wire (1D) and quantum dot (0D) is showed in Fig. 2.3. The DOS for a quantum well is constant between energy intervals. For the ideal quantum dot, there are delta-shaped DOS with no states between the discrete energy levels. That is why the quantum dots are also called as a kind of artificial atoms.

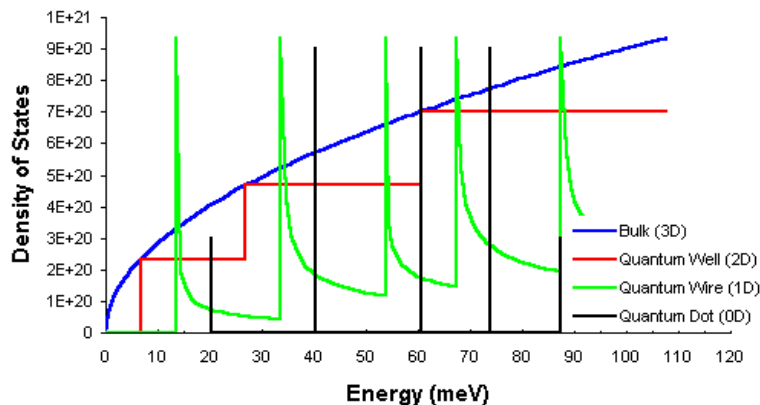


Fig. 2.3. The density of states for bulk, quantum well, quantum wire, and quantum dot (figure obtained from [28])

Besides application for SESAMs with very low saturation fluence, the QD structure is useful for a variety of applications [B3]: in laser diodes with low threshold

pump power or low temperature sensitivity; for white light-emitting diodes (LEDs); for photodetectors; for quantum cryptography (e.g. as single-photon emitters); for quantum computations perhaps. Robust QD structure could provide better performance of output power, which is expected to replace some of the currently used QW structure in SESAMs and laser diodes.

2.3 InAs/GaAs QD SESAM for Diode-pumped PQS Nd-doped 1.3- μm Lasers

Saturable absorbers for short pulse generation in diode-pumped laser at 1.3 μm have attracted considerable interest because of important practical applications such as fiber sensing and intracavity Raman conversion to the 1.5 μm eye-safe spectral region. Currently, the most commonly known saturable absorbers for 1.3 μm Nd-doped lasers include V^{3+} :YAG [2.1], Co^{2+} : MgAl_2O_4 [2], PbS-doped phosphate glasses [3], and semiconductor saturable absorber mirrors (SESAMs) [4]. Previously, two main types of materials for SESAMs at the 1.3 μm wavelength were InGaAs/GaAs and InGaAsP/InP quantum wells [4,5]. InGaAs-based SESAMs for 1.3 μm laser usually lead to significant residual nonsaturable losses because the required indium concentration is beyond the critical strain-thickness limit. Although InGaAsP-based SESAMs could offer absorber layer with smaller lattice mismatch, they have inherent disadvantages such as poor thermal property and lack of proper mirror materials.

To reach the 1.3 μm range wavelength for applications of short-distance fiber-optic communication, two main approaches based on the GaAs material system have been recently proposed. One technique is the use of GaInNAs quantum wells with low nitrogen concentration in an active region [6], the other method is the use of the InAs/GaAs quantum dots multiplayer structures [7]. Very recently, GaInNAs-based SESAMs has been successfully used to mode-lock Nd-doped lasers at 1.3 μm [8,9]. However, to our knowledge, there has been no work on using InAs/GaAs quantum dots to be saturable absorbers in Nd-doped lasers at 1.3 μm . Here, for what is believed to be the first time, a diode-pumped passively Q-switched 1.34 mm Nd:YVO₄ laser with InAs/GaAs quantum dots as a saturable absorber is reported. With an incident pump power of 2.2 W, the compact laser cavity produces an average output power of 360 mW at 1342 nm with a repetition rate of 770 kHz and pulse width of 90 ns.

2.3.1 Three-layer InAs/GaAs QD SESAM Grown by MOCVD

The present InAs/GaAs quantum dot structure was monolithically grown on an undoped GaAs substrate by metalorganic chemical vapor deposition (MOCVD) to simultaneously serve as a SESAM and an output coupler in the passively Q-switched 1.34 μm laser. The Bragg mirror structure consists of 15 AlAs/GaAs quarter-wavelength layers, designed for a reflectivity of 96%. The saturable absorber region were grown at 500 $^{\circ}\text{C}$ to comprise three very thin (3-5 nm) InAs quantum dot layers separated by GaAs half-wavelength layers.

Figure 2.4 shows the measured results for the low-intensity reflectivity and room-temperature photoluminescence (PL) spectrum of the InAs SESAM. The PL peak wavelength was found to be in the vicinity of 1340 nm with a FWHM of 45 nm. It can be seen that the dip in the reflectivity correlates with the maximum in the PL spectrum. One of the advantages over the prior SESAM based on GaInNAs quantum wells is that no annealing is required. It is well known that postgrowth annealing in the GaInNAs SESAM is essentially necessary to reduce nonradiative defects and to tune the PL wavelength close to the lasing wavelength [10,11]. Experimental results reveal that the present SESAM device has modulation depth of 6.7 %, nonsaturable losses of 1.8 %, and a saturation fluence of 25 μJcm^{-2} .

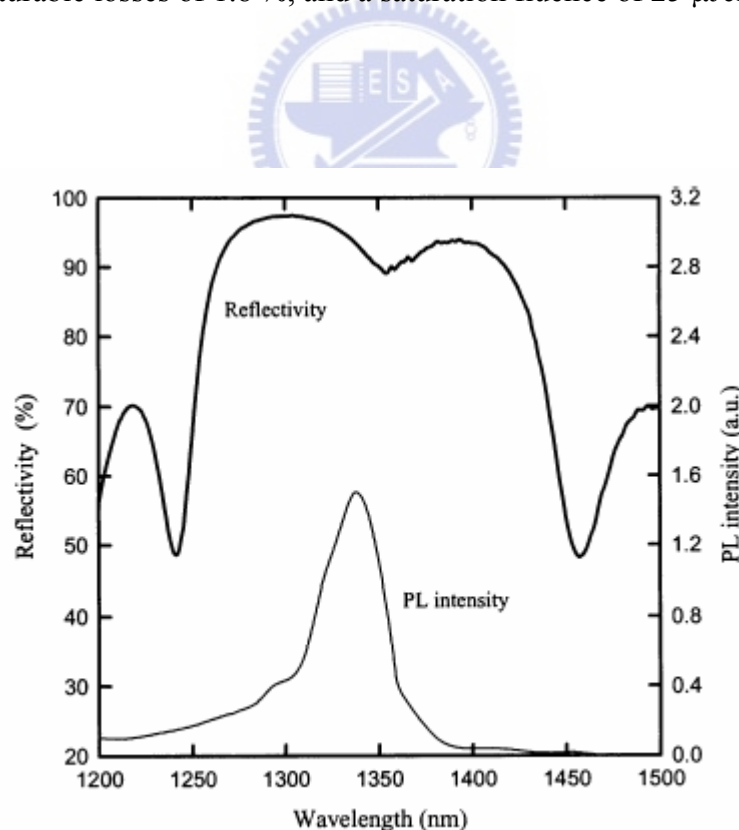


Fig. 2.4. Measured results for the low-intensity reflectivity and room-temperature PL spectrum of the InAs/GaAs quantum-dot SESAM.

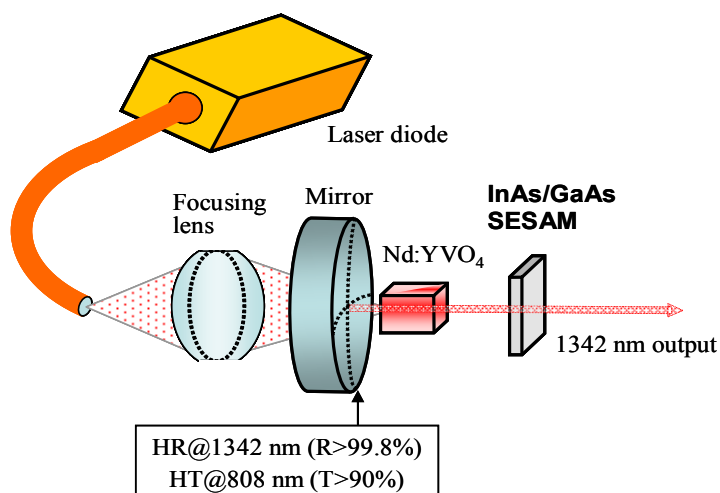


Fig. 2.5. Schematic of a diode-pumped passively Q -switched Nd:YVO₄ laser at 1342 nm: HR, high reflection; HT, high transmission.

2.3.2 Setup and Experiment Result

Figure 2.5 shows the experimental configuration for the passively Q -switched 1.34 μm Nd:YVO₄ laser by use of InAs/GaAs quantum dots as a saturable absorber and an output coupler. The active medium was a 2.0 at.% Nd³⁺, 1-mm-long Nd:YVO₄ crystal. Both sides of the laser crystal were coated for antireflection at 1.34 μm ($R < 0.2\%$). The pump source was a 2.5-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, M1, 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 very near the input mirror for the spatial overlap of the transverse mode structure and radial pump power distribution. The overall Nd:YVO₄ laser cavity length was approximately 20 mm. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer employing diffraction lattice monochromator can be used for high-speed measurement of pulse light with the resolution of 0.1 nm. The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gs/sec, 1 GHz bandwidth) with a fast PIN photodiode.

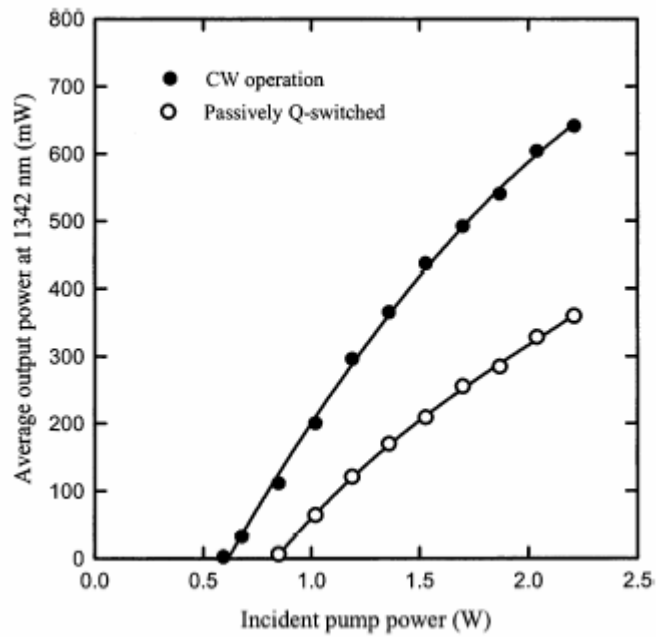


Fig. 2.6. Average output powers at 1342 nm with respect to the incident pump power in cw and passive Q -switching

The cw performance of the Nd:YVO₄ laser at 1342 nm was studied first. For this investigation an output coupler with partial reflection at 1342 nm was used instead of the above-mentioned InAs quantum dots SESAM. The optimum reflectivity of the output coupler was found to be approximately 94%. The optimum cw performance at 1342 nm provides the baseline for evaluating the passively Q -switched efficiency. Figure 2.6 shows the average output powers at 1342 nm with respect to the incident pump power in cw and passively Q -switching operations. In the cw regime the laser had a slope efficiency of 40%; the output power reached 640 mW at an incident pump power of 2.2 W. In the passively Q -switching regime an average output power of 360 mW was obtained at an incident pump power of 2.2 W. The Q -switching efficiency (ratio of the Q -switched output power to the cw one at the maximum pump power) was estimated to be 56%. This Q -switching efficiency is considerably higher than the results of 1.3 μm lasers with other known absorbers [1-4,12]. The superior performance indicates that the nonsaturable losses of the present InAs quantum dots SESAM are relatively low.

Figure 2.7 shows the pulse repetition rate and the pulse width versus the incident pump power. The pulse repetition rate initially increases with pump power, and is almost saturated at approximately 770 kHz beyond 1.6 W of the incident pump power. On the other hand, the pulse width decreases from 360 ns at threshold to 90 ns at 2.2

W of incident pump power. As a consequence, the peak power was found to be higher than 5 W. A typical oscilloscope trace of a train of output pulses and an expanded shape of a single pulse are shown in Fig. 2.8. Under the optimum alignment condition, the pulse-to-pulse amplitude fluctuation was found to be within $\pm 10\%$.

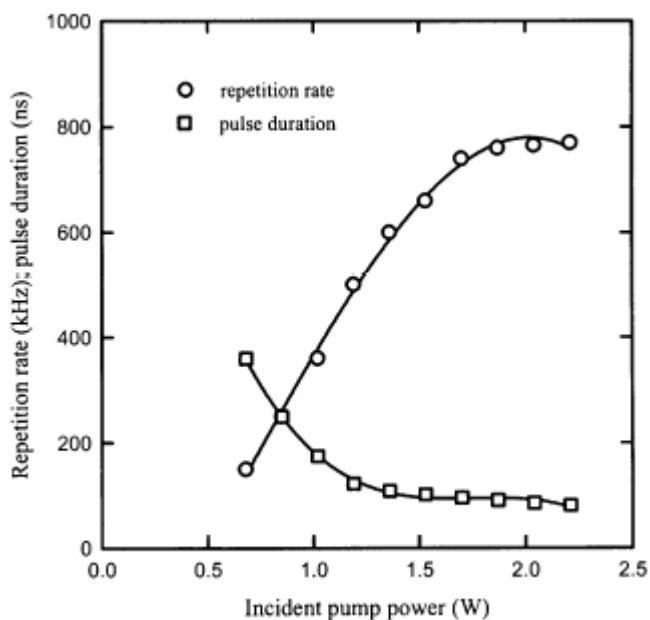


Fig. 2.7. Experimental results for pulse repetition rate and pulse width versus incident pump power.

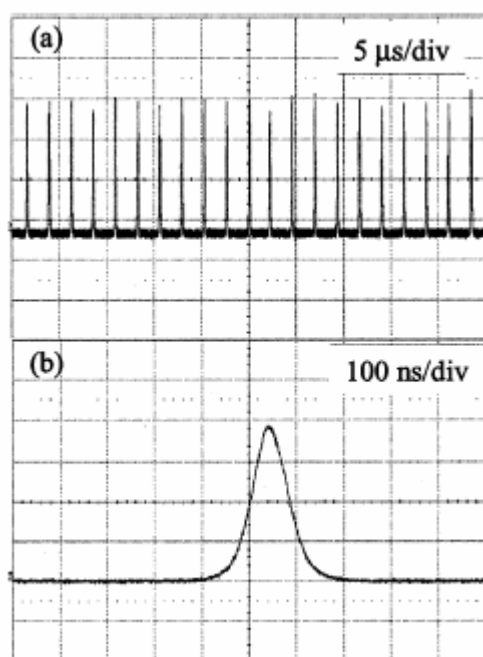


Fig. 2.8. (a) Typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

2.4 InAs/GaAs QD SESAM for a Passively Mode-locked Nd:YVO₄ Laser at 1342 nm

Semiconductor saturable absorber mirrors (SESAMs) have been identified as promising saturable absorbers for passively mode-locked all-solid-state lasers [2.13-2.16]. In the past decade, most SESAMs were focused in the 0.8–1.06- μm spectrum region. The applications such as fiber sensing and intracavity Raman conversion to the 1.5- μm eye-safe spectrum region have enabled the high-peak-power solid-state lasers at 1.3 μm to be a practical light source [17,18]. Previously, two main types of materials for SESAMs at the 1.3- μm wavelength were InGaAs/GaAs and InGaAsP/InP quantum wells [4,5]. InGaAs-based SESAMs for 1.3- μm lasers usually lead to significant residual nonsaturable losses because the required indium concentrations are beyond the critical strain-thickness limit. On the other hand, InGaAsP-based SESAMs could offer absorber layers with smaller lattice mismatches; however, they have inherent disadvantages such as low thermal conductivity and scarcity of suitable mirror materials.

Recently, two new schemes based on the GaAs material system have been proposed to reach a wavelength near 1.3 μm for applications of short-distance fiber-optic communication. One technique is the use of GaInNAs quantum wells (QW) with low nitrogen concentration in an active region [6], the other approach is the use of the InAs/GaAs quantum dots (QD) multiplayer structures [7,19]. GaInNAs-based SESAMs have been lately applied to mode lock Nd-doped lasers at 1.3 μm [8,9]. More recently, the QD-SESAM has been successfully used as a saturable absorbers in a passively mode-locked Yb:KY(WO₄)₂ laser at 1.03 μm [20]. Even so, to our best knowledge, no experiments employing InAs/GaAs QDs to mode lock solid-state lasers near 1.3 μm have been reported. In this section, we demonstrate a diode-pumped self-starting continuous mode-locked Nd:YVO₄ 1.34 μm laser with an InAs/GaAs QD-SESAM. With an incident pump power of 12.6 W, the mode-locked laser cavity produces an average output power of 0.85 W at 1.34 μm with a pulse width around 26 ps.

2.4.1 Cavity Design and Setup

The QD-SESAM structure, used as an output coupler in the mode-locked 1.34- μm laser, was grown on an undoped GaAs substrate by metalorganic chemical vapor deposition (MOCVD). The Bragg mirror structure was composed of 15 AlAs/GaAs quarter-wavelength layers. The reflectivity of the QD-SESAM was measured to be 92%. The saturable-absorber part comprised three very thin (3-5 nm)

InAs QD layers separated by GaAs half-wavelength layers. The growth temperature of the absorber structure was 500°C.

Figure 2.4 depicts the measured results of the room-temperature photoluminescence (PL) spectrum for the QD-SESAM. It can be seen that the PL peak wavelength is in the vicinity of 1340 nm with a FWHM of 45 nm. Unlike the saturable absorber based on GaInNAs quantum wells, there is no need to anneal the QD-SASEM to tune the PL wavelength. Postgrowth annealing is an essential process for GaInNAs SESAM to reduce nonradiative defects and to tune the PL wavelength close to the lasing wavelength [10,11]. Experimental results indicated that the present QD absorber has a saturation fluence of 20 $\mu\text{J}/\text{cm}^2$, a modulation depth of 3.0%, and nonsaturable losses of 2.0%.

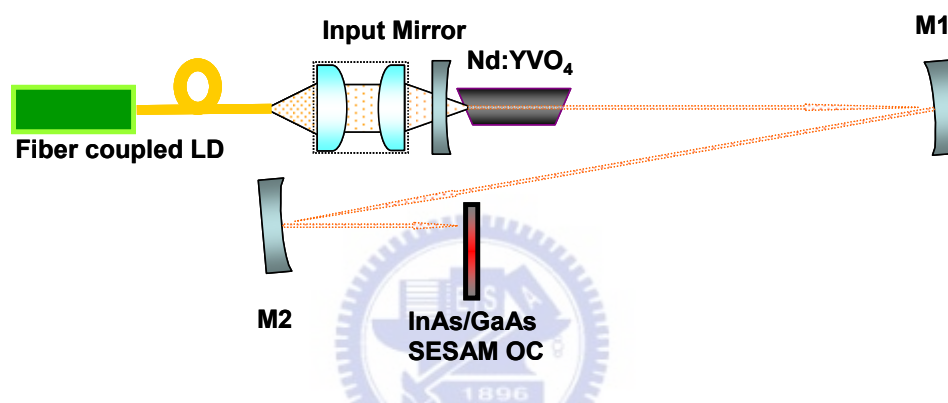


Fig. 2.9. Schematic of a diode-pumped self-starting continuous-mode-locked Nd:YVO₄ laser at 1342 nm: LD, laser diode; OC, output coupler.

Figure 2.9 shows the experiment configuration for the CML 1.34 μm Nd:YVO₄ laser by use of InAs/GaAs quantum dots as a saturable absorber and an output coupler. The gain medium was a 3.0% Nd³⁺, 9-mm-long Nd:YVO₄ crystal. Both sides of the laser crystal were coated for antireflection at 1.34 μm ($R < 0.2\%$) with the wedge-cut angle of 0.5 degree. The pump source was a 16-W 808-nm fiber-coupled laser diode with a core diameter of 800 μm and a numerical aperture of 0.2. Focusing lenses unit with 17.5 mm focal length and 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius was around 350 μm . The resonator consisted of one input mirror, two high-reflection concave mirrors at lasing wavelength ($R > 99.8\%$), M1 and M2, and one QD-SESAM as an output coupler. The input mirror was a 500 mm radius-of-curvature concave mirror with antireflection coating at the diode wavelength ($R < 0.2\%$) on the entrance face, high-reflection coating at the lasing wavelength ($R > 99.8\%$), and high-transmission coating at the

diode wavelength ($T > 90\%$) on the other face. Note that the laser crystal was placed very close to the input mirror for a spatial overlap of the transverse mode structure and radial pump power distribution. The radii of curvature for M1 and M2 are 500 mm and 100 mm, respectively. M1 and M2 were separated by 600 mm; the overall cavity length was approximately 1000 mm. The laser mode radii were calculated to be 345 μm inside the laser crystal and 42 μm on the QD-SESAM. The QD-SESAM is simply mounted upon a copper heat sink but no active cooling is applied.

2.4.2 Experiment Result

To provide the baseline for evaluating the mode-locking efficiency, the cw performance of the present laser at 1342 nm was studied first. For this investigation an output coupler with partial reflection at 1342 nm was used instead of the InAs QD-SESAM. The optimum reflectivity of the output coupler was found to be approximately 94%. Figure 2.10 illustrates the average output power at 1342 nm with respect to incident pump power in cw operation (solid circles) and cw mode-locking operation (open circles). In the cw regime the laser had a slope efficiency of 15%; the output power reached 1.31 W at an incident pump power of 12.6 W. With QD-SESAM as an output coupler, the laser self-started the cw mode-locking operation at the pump powers greater than 3.95 W. In the cw mode-locking operation, the laser, as showed in Fig. 2.10, had a slope efficiency of 9.8%; the output power reached 0.85 W at an incident pump power of 12.6 W.

The cw mode-locking pulse train was recorded by the LeCroy digital oscilloscope (Wavepro 7100, 10 Gs/sec, 1 GHz bandwidth) with a fast PIN photodiode. Figure 2.11 shows the typical pulse train of the cw mode-locked laser. It can be seen that the pulse period of 6.6 ns is consistent with the roundtrip time of the cavity length. The temporal duration of the mode-locked pulses was measured to be approximately 26 ps. The spectral information of the laser was monitored by an optical spectrum analyzer (ADVANTEST Q8347) with the resolution of 0.005 nm. The spectral bandwidth (FWHM) was found to be 0.101 nm. This result implied the time-bandwidth product was approximately 0.44.

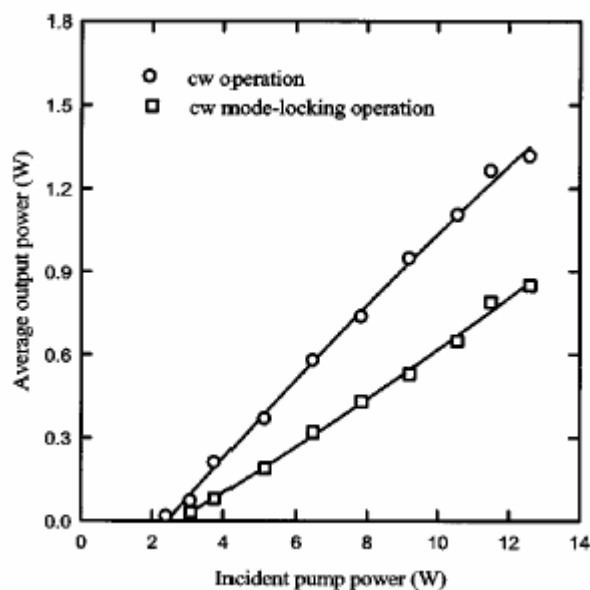


Fig. 2.10. Average output power at 1342 nm versus incident pump power in cw and mode-locking operation.

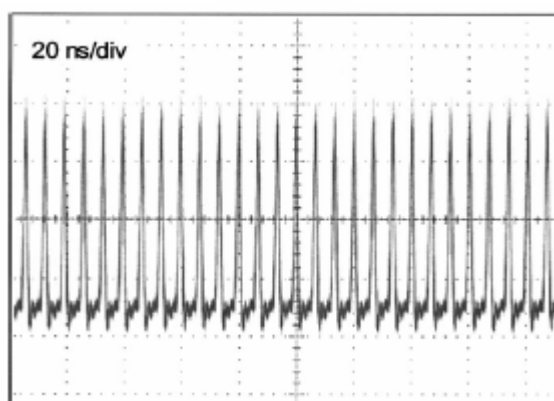
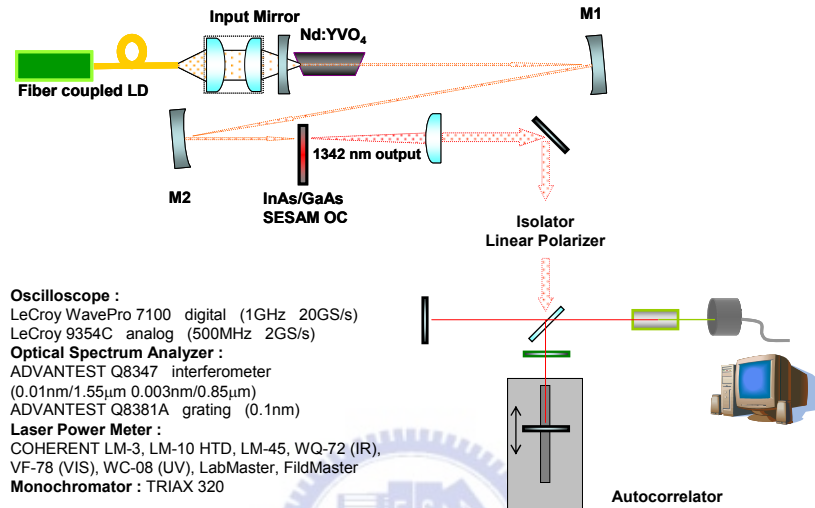


Fig. 2.11. Typical oscilloscope trace of a train of output pulses.

It is worthwhile to make a comparison between the present performances and the previous result with GaInNAs QW as a saturable absorber [9]. The present slope efficiency is lower than the result of 18% with a GaInAs QW absorber. The lower slope efficiency is mainly attributed to the nonoptimization of the output coupling of QD-SESAM and the nonsaturable losses. The conversion efficiency is expected to improve considerably by optimizing the output coupler and reducing the nonsaturable losses. Even so, the maximum output power of 0.85 W obtained here is higher than the previous result of 0.52 W. On the other hand, the present lasing bandwidth of 0.1 nm is approximately 1/4 times the bandwidth of 0.39 nm obtained in Ref. 12. As a

consequence, the pulse width of 26 ps is roughly four times the pulse width obtained in Ref. 12. The narrower bandwidth might come from the additional etalon effects introduced by using QD-SESAM as an output coupler. It is expected the etalon effects can be effectively avoided by using a high quality antireflection coating ($R < 0.2\%$) on the backside of the GaAs wafer. Nevertheless, the use of SESAM to be an output coupler can make laser systems easier and more compact for practical applications [21].



2.5 Conclusion and Future Work

We constantly devote our attention to the transmissible SESAM that can be acted as an OC, which may have more potential on applications. InAs/GaAs quantum dots were used to be a low-loss semiconductor saturable-absorber output coupler for the Q-switching of a diode-pumped Nd:YVO₄ laser operating at 1342 nm. An average output power of 360 mW with a Q-switching efficiency of 56% was obtained at an incident pump power of 2.2W. Stable Q-switched pulses of 90 ns duration with a repetition rate of 770 kHz were generated. The result indicated the possibility of using InAs/GaAs quantum dots structure to mode-lock a Nd-doped laser at 1.3 μ m.

As expected, then we demonstrated a diode-pumped self-starting continuous mode-locked Nd-doped 1.34 μ m laser by use of InAs/GaAs QD-SESAM. With QD-SESAM as an output coupler, an average output power of 0.85 W was obtained at an incident pump power of 12.6 W. Stable pulses around 26 ns duration with a repetition rate of 152 MHz could be reached. The present results including [29] published by A. McWilliam et al. in 2006 indicate that the InAs/GaAs QD structures are the appropriate saturable absorbers to mode lock Nd-doped lasers around 1.3 μ m.