Novel use of GaAs as a passive Q-switch as well as an output coupler for diode-pumped infrared solid-state lasers

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ABSTRACT

Q-switched operation is very common and important for diode-pumped solid-state lasers. In this paper, we reported a novel use of GaAs wafers as Q-switch elements as well as output couplers for DPSS lasers. A pulse duration of 2.6 ns at the wavelength of 1064 nm was obtained from a diode-pumped and passively Q-switched Nd:YVO_4 laser using a piece of GaAs wafer as the saturable absorber as well as the output coupler. The transmissivity and the absorption coefficient of different wafers were studied. The experimentally measured results indicated that the transmssivity of different GaAs wafers varied from as low as ~32 % to as high as ~75 %. It was found that some of those wafers showed Fabry-Perot effect and it could affect the effective transmissvity and produce lower transmission, and thus shorten the pulse duration and stabilize the laser operation.

Key words: solid-state lasers, passive Q-switching, GaAs, diode-pumping.

1. INTRODUCTION

Q-switched operation is very common and important for diode-pumped solid-state (DPSS) lasers. Q-switching of lasers can provide short pulses with high peak power, thus it has many applications in the fields of non-linear optics, range finding, medicine, and micromachining[1]. Passive Q-switching, without extra power supply and driving, has attracted much research attention in recent years, especially for diode-pumped solid-state lasers[2, 3]. In the previous work, we demonstrated passive Q-switching using undoped and uncoated GaAs wafers as Q-switch elements as well as output couplers for several laser systems[4-6]. This kind of Q-switching has many advantages in lowering cost, shortening laser cavity, simplifying laser operation, and improving the compactness of laser system.

In this paper, we reported more detailed study on the optical properties of GaAs wafers such as transmission and saturable absorption, and the characteristics of a passively Q-switched diode-pumped Nd:YVO_4 laser using several different GaAs wafers. In the previous studies, we utilized two different theoretic models, i.e., F-P model[7] and energy-level model[5], to simulate the pulse temporal profile of the passively Q-switched laser operation. We found that both the effects had an influence on the saturable absorption of GaAs wafers. Therefore, a more detailed analysis on it was carried out in the present work.

2. OPTICAL ABSORPTION PROPERTIES OF GAAS

2.1 Theoretical analysis

We are mainly concerned with the optical properties of GaAs because we had used it as a saturable absorber for the passive Q-switching of a laser system in this paper. GaAs has been one of the most widely used semiconductors. GaAs wafers are made up of bulk single crystals. Single GaAs crystals are grown from the melt by means of either horizontal Bridgman, gradient freeze, or liquid encapsulated Czochralski (LEC), etc[8]. In this particular study, we mainly concern about the

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absorption property of GaAs. For semiconductors, the fundamental absorption involves excitation of an electron from the valence band to an empty state in the conduction band. The absorption increases with the increase in photon energy of incident light. As the photon energy approaches the band gap, E_g, the absorption increases rapidly as much as 3 to 4 orders of magnitude and $h\nu \approx E_g$ represents the fundamental absorption edge. GaAs is a direct band gap semiconductor with E_g = 1.42 eV. That implies that no absorption is to be expected for photon energy below 1.42 eV for GaAs. However, the absorption coefficient decreases more slowly below the fundamental edge than that suggested from the theory. It is believed that the absorption below E_g is related to impurities and photon-assisted transitions, i.e., impurities participate in the absorption process at $h\nu < E_g$. The photon energy of the laser beam at the wavelength of 1.06 μm is 1.17 eV, which is lower than the band gap energy of GaAs. Therefore, the absorption of GaAs at the wavelength of 1.06 μm involves in the above mechanism, which is associated with the EL2 centers in GaAs[8].

The Fermi level of undoped semi-insolating GaAs is pinned near the middle of the band gap by a deep donor center which is labeled as EL2 level. This center is now believed to be formed entirely due to the intrinsic point defects. The concentration of EL2 depends on the melt stoichiometry, increasing from about 5×10^{15} cm^{-3} to 1.7×10^{16} cm^{-3} as the As atom fraction is increased from 0.48 to 0.51.

The existence of EL2 deep levels was first established from deep-level spectroscopic data obtained by thermally simulated current measurements and by deep-level transient spectroscopy (DLTS). From the Arrhenius temperature dependence of the electron emission rate of EL2, an activation energy of 0.825 eV is obtained. The temperature dependence of the electron capture rate has been measured and found to have an activation energy of 0.066 eV. From the detailed balance we have that the EL2 level must lie 0.76 eV below the conduction band[8]. The results thus demonstrate that EL2 is a mid gap level.

The optical absorption coefficient of undoped GaAs has mainly been affected by EL2 concentration. EL2 defects occur in bulk crystals grown by LEC and the Bridgman technique, and are more easily formed under As rich conditions. Mainly contributed by two-photon-absorption and free-carrier-absorption, GaAs has the property of saturable absorption at the wavelength of 1.06 μm, which implies that it can be used as a saturable absorber for passive Q-switching .

The absorption coefficient a of GaAs can be expressed as[5]

$$a = s_{\mathrm{e}}(N_{\mathrm{t}} - N^{+}) + s_{\mathrm{h}} N^{+} + s_{\mathrm{fc}} n , \qquad (1)$$

where s_e is the cross section of EL2 absorption, N_t is the total density of EL2 level, N^+ is the portion of the positively charged EL2 centers, i.e., $EL2^+$, s_h is the cross section of $EL2^+$ absorption, s_{fc} is the cross section of free carrier absorption (FCA), and n is the density of the free electrons produced by the transition from EL2 to the conduction band after the absorption of the optical energy of the incident laser beam.

From equation (1) we can see that, when the intensity of the incident light is low, both N^+ and n will be low and hence it can be ignored. Thus the absorption coefficient α equals to $s_e N_t$, which represents the linear absorption of GaAs at low inrradiance region, and equals approximately to 1.1 to 1.2 cm^{-1} at the wavelength of 1.06 μm, which is determined only by σ_e and N_t. This value is much lower than that of the absorption for light with the photon energy higher than the band gap energy, which is in the order of 10^3 to 10^4 cm^{-1}. With the increase in the intensity of the incident laser beam, more EL2 centers will be positively charged, i.e., N^+ will increase, and thus makes the absorption coefficient lower than its linear absorption coefficient. Once the intensity of the incident laser beam becomes high enough, the decreasing of the absorption coefficient caused by the increasing of N^+ will be surpassed by the increasing caused by the FCA when n becomes very high under the irradiation of high intensity laser beam. Then, the absorption coefficient will increase and higher than its linear absorption coefficient. This kind of the variation of absorption coefficient represents the characteristics of the saturable absorption of GaAs, i.e., its nonlinear optical properties. We simulated the process by incorporating the rate equations and the results are presented and discussed later in Section 4.

For GaAs wafers, optically polished on its both surfaces, multiple surface reflecting and multiple interfering among the reflected beams sometimes can not be neglected because they change the total nonlinear optical effect of the wafer. In this case, the wafer becomes a Fabry-Perot (F-P) cavity filled with a nonlinear medium, i.e., a nonlinear F-P cavity, and the effective reflection, absorption and transmission exhibit a series of maxima and minima[9]. For a certain wavelength, refractive index and the surface reflection, the optical properties will be more sensitive to the thickness of the wafer (variation in the order of the wavelength of the incident light) if the F-P effect exists. Since the absorption of GaAs has the characteristics of saturable absorption, it makes the effective reflection and transmission.

2.2 Experimental study

For the application of using GaAs wafers as passive Q-switches as well as output couplers in a laser system, the properties of transmission as well as the saturable absorption of GaAs are more important. We have found that wafers from the same supplier have totally different optical properties. The thickness and doping conditions of four different wafers were studied as listed out in Table 1. They were all optically polished on both the sides and have no extra coating, with an orientation of (100)±0.3°. Wafers #1 and #2 were undoped, and wafers #3 and #4 were Si doped with a doping concentration of 1.9 ~ 3.7 $\times 10^{18}$ cm^{-3}.

To measure the transmissivity of the GaAs wafers, an acoustic-optically (A-O) Q-switched laser was employed. It provided Q-switched pulses of 150 ns in pulse duration, 90 kHz in pulse repetition rate and 101 m W in averaged output power. The measured transmissivity of the wafers, as indicated in Table 1, varied in a relatively large range from as low as 32 % to as high as 75 % at normal incident angle for different wafers. Since the GaAs wafers were also used as the output couples of the laser cavity, the transmissivity at the normal incidence has been the most important for the application.

Table 1. Results of the transmissivity measurement of GaAs wafers

S/N	Thickness (µm)	Doping	Transmissivity (%) (at normal incidence)	F-P effect
# 1	625	Undoped	32	Yes
# 2	500	Undoped	75	No
# 3	635	Si-doped	55	No
# 4	350	Si-doped	64	Yes

By employing an NEWPORT Motion Controller MM 3000 (with an angler resolution of 0.01°), the variation of the transmissivity of the GaAs wafers with the variation in incident angles of the laser beam were measured. The results were plotted in Fig. 1. It is found that wafer #1 has the lowest transmissivity, ~ 32 %, at the normal incidence with an obvious periodical variation in transmissivity with the variation in the incident angle. Wafer #2 has the highest transmissivity, ~ 75 %, at the normal incidence, but no periodical tendency of variation in transmissivity observed only a transmissivity peak at the normal incidence. The characteristics of wafer #3 is similar to that of wafer #2, but with a lower transmissivity, ~ 55 %, at the normal incidence. Wafer #4 is similar to wafer #1, but with a much high transmissivity, ~ 64 % at the normal incidence and the periodical variation tendency is not so obvious.

The results shown in Fig.1 indicate that wafers #1 and #4 have the F-P effect but wafers #2 and #3 did not. It is found that the transmissivity of the wafers at normal incidence have no direct relation to their thickness and doping conditions, but is mainly affected by F-P effect. Our study shows that the property of transmissivity as well as the F-P effect have a large impact on the performance of the passively Q-switched operation of the laser system.

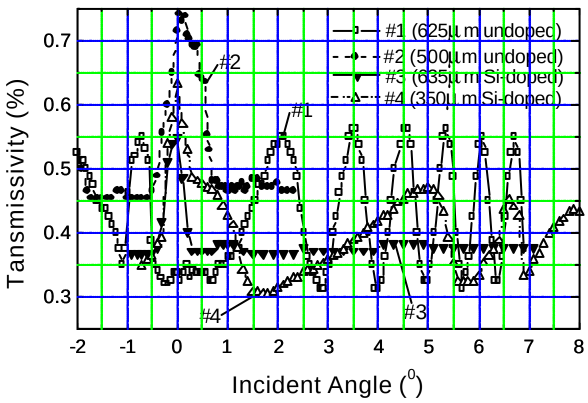

Fig.1 The measured transmissivity of GaAs wafers with the variation in incident angle

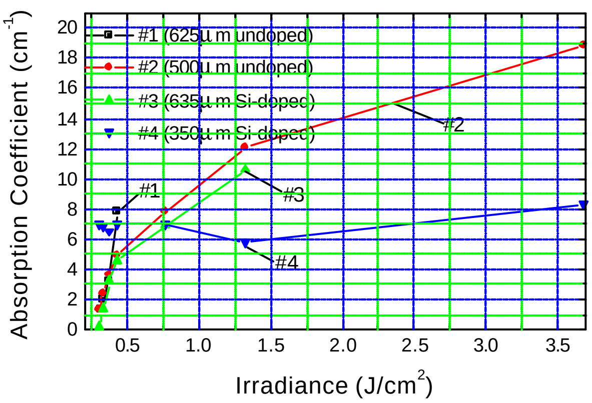

Fig. 2 the measured absorption coefficient of GaAs wafers with the increase in the intensity of the incident laser beam

Generally, the absorption coefficient of semiconductor wafers is experimentally measured from their transmissivities and then calculated based on the information of their surface reflectivity and thickness. Fig.2 shows the results of the measured absorption coefficient for the 4 GaAs wafers with the increase in the intensity of the incident laser beam. The incident laser beam was an A-O Q-switched pulse with 5 ns in pulse duration and 65 mJ in single pule energy provided by a lamp -pumped Nd:YAG laser at the wavelength of 1.06 μm. The laser beam was focused onto the wafers in normal incidence. We fixed the operation conditions of the laser system during the testing. By changing the de-focusing to change the laser beam size on the surface of the wafer, and thus by which to vary the intensity of the incident laser beam.

The results shown in Fig. 2 perhaps are not so accurate because we did not have the accurate information about the surface reflectivity of the wafers. But some information provided in Fig. 2 could be more useful for the study. Wafer #1 has been more sensitive to the increase in the intensity of the laser beam, which means that it has the good property of saturable absorption. The values of the irradiance corresponding to the last point of each curve in Fig. 2 represent the threshold of the surface melting of the GaAs wafers. This implies that the GaAs wafers could be used in high power/energy laser systems without damage. With high transmissivity, high in the melting threshold.

3. PASSIVE Q-SWITCHING OF A DIODE-PUMPED ND:YVO_4 LASER

We studied on the Ga As wafers as the passive Q-switches as well as its output couplers in a diode-end-pumped DPSS laser system. Fig. 3 shows the experimental layout. A fiber-coupled diode laser was used to pump an Nd:YVO_4 laser crystal. The diode laser was an OPC-15FC type providing a CW laser beam at 808 nm. The pumping beam was the output from an optical fiber and firstly collimated and then focused onto the laser crystal. The crystal was in the dimension of 3 mm × 3 mm × 5 mm, an Nd doping concentration of 1.1 %, and one facet AR coated at 808 nm and HR coated at 1064 nm, which served as the end mirror of the laser cavity. The opposite facet of the crystal was AR coated at 1.06 μm. A piece of GaAs wafer was placed on the other side, serving as a passive Q-switch as well as an output coupler and forming a laser cavity of 6 mm in length. There was no active cooling for the GaAs wafer.

The Q-switched laser pulses were obtained by carefully aligning the laser cavity. The averaged output power was measured by using a power meter. The pulse duration and the pulse repetition rate were detected by using a THORLABS 7227 fast photon detector and recorded using a Tektronix TDS 360 oscilloscope. Fig.4 shows the variation of the averaged output power with the increase in pumping power. The best performance was provided by wafer #1, which was with the lowest transmissivity and enhanced by F-P effect. It had the lowest lasing threshold, ~2.6 W, and the highest output power, ~ 520 mW, corresponding to an optical-to-optical efficiency of 7.4 %. Other wafers showed higher threshold and lower output power. When compaed to the wafers #3 and #4, it was also found that the F-P effect had the influence on the laser operation. For wafer #2, the output power was very low and even found to decrease with the increase in pumping power. The cavity alignment was very different for it because it was too sensitive for adjustment. This was perhaps caused by its very high transmissivity at the normal incidence, and it hence unsuitable for this kind of application.

Fig. 5 illustrates the variation of the measured pulse duration with the increase in the pumping power. The pulse duration decreased with the increase in the pumping power, and we did not detect any saturation tendency for the pulse duration. It is found that GaAs wafer #1 produces the shortest pulse duration and stable operation, mainly because of the lowest transmission and the enhancement by F-P effect. Its pulse duration did not change so much, about 3 to 5 ns, under high intensity pumping (pumping power > 4 W).

Wafers #2, #3 and #4 produced very long pulses and very sensitive to the adjustment of laser cavity, thus resulting with low performance. The pulse duration was from several hundred nanosecond at high pumping intensity to nearly one microsecond at low pumping intensity near the lasing threshold. The pulse repetition rate was from several hundreds kHz to about 1 MHz. According to the recorded pulses' oscilloscope traces, it was found that the outputs from wafers #2, #3 and #4 consisted of CW signals except for Q-switched pulse signal, and, especially for wafer #2, most of the output laser beam was CW.

The shortest pulse duration produced by wafer #1 was 2.6 ns with a pulse repetition rate of about 300 kHz at a pumping power of 5.2 W. Fig. 6 shows the oscilloscope trace of both the single pulse and the corresponding pule train at the same operation condition. The small fluctuation follows the pulse at zero-level is believed to be caused by the electronic circuit of the detector at such rapid time responding. At the low pumping level with longer pulse duration, this kind of fluctuation did not arise.

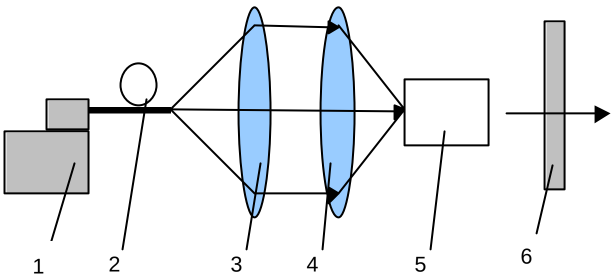

Fig. 3 Experiment layout for the DPSS laser.
1-diode laser, 2-optical fiber, 3-collimating lens, 4-focusing lens, 5-laser crystal, 6-GaAs wafer.

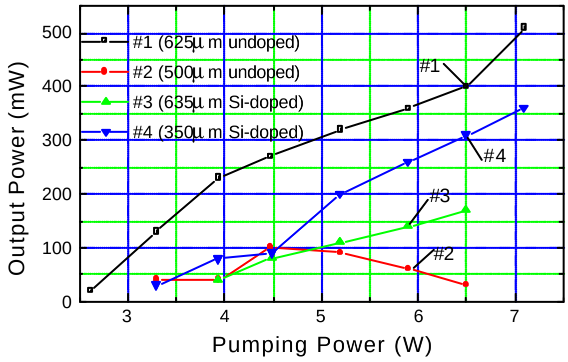

Fig.4 Averaged output power for different GaAs wafers

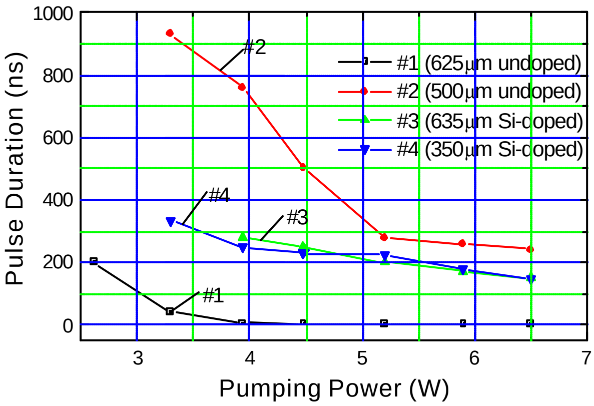

Fig. 5 Variation of pulse duration with the increase in pumping power for different wafers.

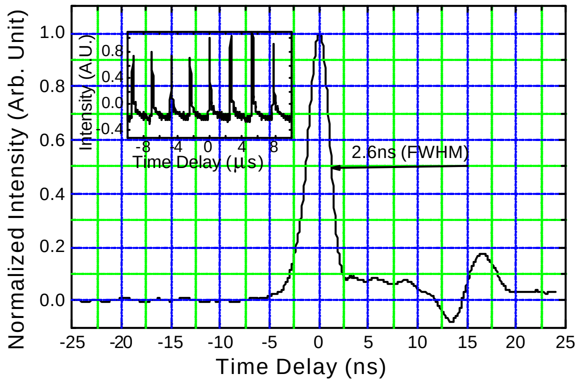

Fig. 6 A pulse of 2.6 ns in pulse duration and a pulse train of 300 kHz in pulse repetition rate produced by the passive Q-switching using wafer #1.

4. SIMULATION

In order to simulate the pulse temporal profile of the Q-switched laser operation when a piece of GaAs wafer is being used as the passive Q-switch as well as the output coupler, we employed an energy level model to simulate a diode-side-pumped Nd:YAG laser [5], and an F-P model to simulate a diode-end-pumped Nd:YVO_4 laser in the previous studies[7]. However, when F-P effect exists, we need tocombine these two models, i.e., both of the saturable absorption contributed by TPA and FCA of the EL2 level in the energy-level model and the nonlinear reflection and transmission contributed by F-P effect in the F-P model should be considered in the rate equations for the laser operation.

Illustrated in Fig.7 is a typical result simulated by combining the two theoretical models mentioned above using the conventional rare equations in the laser cavity and the rate equations within the GaAs wafer of 625 μm in thickness, where f is the photon density (cm^{-3}) in the laser cavity, N is the population inversion density (cm^{-3}) in the laser crystal, and p is the density of holes produced by the transitions of valence to $EL2^+$ level in GaAs wafer. Other parameters are defined as he same as those in Eq. (1), all the equations and constant parameters were given in Ref.5 and Ref. 7. The only difference was that we expressed the loss of the laser cavity by combining the saturable absorption and the F-P effect as mentioned above. The initial values of f, N, n, p, N^+ and α for the simulation were 1.0×10^{-3} cm^{-3}, 3.6×10^{18} cm^{-3}, 1.0×10^{7} cm^{-3}, 1.0×10^{7} cm^{-3}, 1.4×10^{15} cm^{-3} and 1.2 cm^{-1}, respectively.

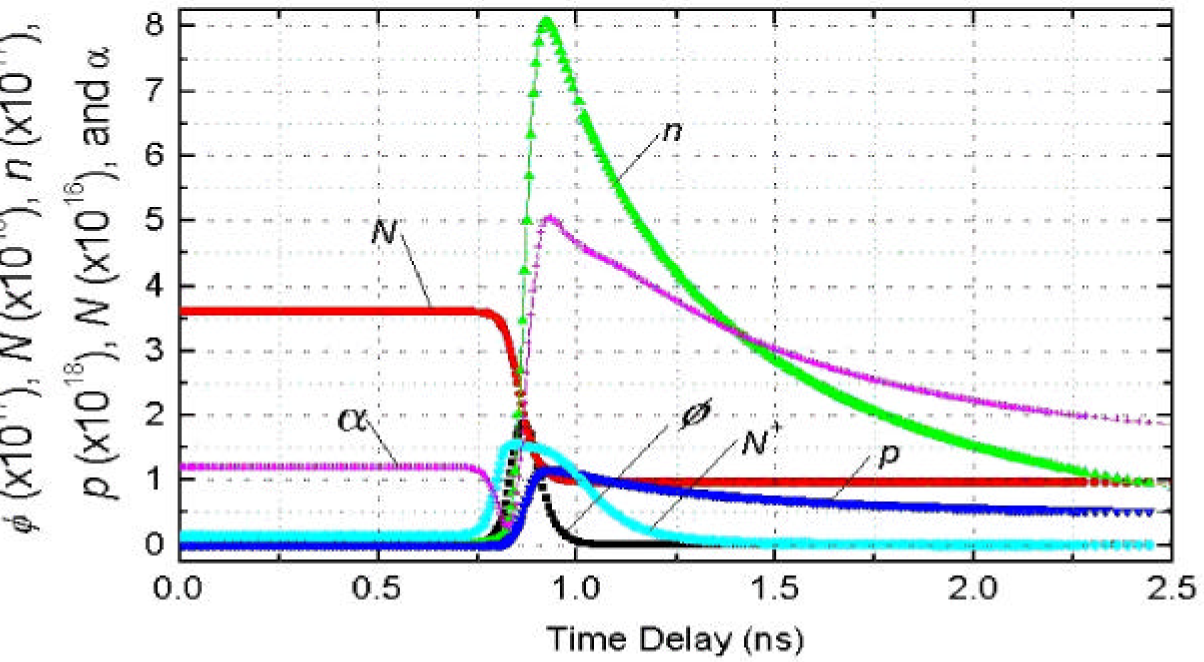

Fig. 7 simulated results using the combined F-P and energy-level models

According to the simulated results, it is found that the absorption coefficient decreases from its initial value of 1.2 cm^{-1} to as low as about 0.3 cm^{-1} when the photon density increases to its half maximum, about 1.0×10^{17} cm^{-3}. This means that the saturable absorption of GaAs contributes to the development of the Q-switched pulse. The absorption coefficient then increases to its maximum of about 5.0 cm^{-1} with the increase in photon density, which was mainly caused by the repaid increase in FCA under irradiation of higher intensity, and begins to decrease after the photon density decreases to zero. The fact that the simulated absorption coefficient is much high than its linear value under the irradiation of laser beam with very high intensity is in reasonable agreement with the experimentally measured values as illustrated in Fig.2.

5. CONCLUSION

In summary, we studied the transmission and absorption properties of four different kinds of GaAs wafers, with different thickness and different doping conditions. It was found that some of the wafers showed a periodical variation of transmissivity with the variation in incident angle, which was caused by the optical F-P effect. The measured transmissivity at the normal incidence varied from ~32 % to ~ 75 % for different wafers, showing no direct relation to the thickness of the GaAs wafers for those studied in the present work.

By using the GaAs wafers as saturable absorbers as well as output couplers, a diode-end-pumped Nd:YVO4 laser was demonstrated. The variations of the pulse duration and the averaged output power with the increase in pumping power were presented. When comparing the results of the passive Q-switching by using the above different GaAs wafers, the undoped wafer of 625 μm in thickness produced the shortest pulse duration, 2.6 ns, and the highest output power, 520 mW. It was found that the transmissivity of the GaAs wafers had a grate influence on the performance of the passive Q-switching, and the thickness of the wafer had no much influence when varied within a certain range. The experimental results have shown that F-P effect could enhance the saturable absorption and stabilize the laser operation.

We used the combined F-P model and the energy-level to simulate the Q-switched pulse temporal profile and the saturable absorption coefficient. The results indicated that the absorption coefficient of GaAs decreased from its linear value, ~ 1.2

cm^{-1}, to ~ 0.3 cm^{-1} under the irradiation of laser beam, and increased to about 5.0 cm^{-1} under the irradiation with higher intensity due to FCA.

Passive Q-switching using a piece of GaAs wafer as a saturable absorber as well as an output coupler provided a novel technique for compacting the laser cavity and simplifying the laser system for a DPSS laser. It is believed that this kind of technology could be used in the development of other infrared solid-state lasers with the wavelength from 1 to 2 μm.

REFERENCES

1. A. Agnesi, S. Dell'Acqua, C. Morello, G. Piccinno, G. C. Readi, and Z. Sun, "Diode-pumped neodymium lasers repetitively Q-switched by Cr^{4+}:YAG solid-state saturable absorbers," *IEEE J Sel. Top. in Quantum Electron*., **3**, pp. 45-52 , 1997.
2. Y. F. Chen, T. M. Huang, and C. L. Wang, " Passively Q-switched diode-pumped Nd:YVO_4 /Cr^{4+}:AYG single-frequency microchip laser," *Elecron. Lett*., **33**, pp. 1880-1881, 1997.
3. A. Agnesi, S. Dell'Acqua, E. Piccinini, G. Reali, and G. Piccinno, " Efficient wavelength conversion with high-power passively Q-switched diode-pumped neodymium lasers," *IEEE J Quantum Electron*., **34**, pp. 1480-1484, 1998.
4. J. Gu, F. Zhou, S. C. Tam, W. Xie, Y. L. Lam, and Y. Chen. " Passive Q-Switching of a Nd:YAG laser with a GaAs output coupler" , *Opt. Eng*. **38** (11), 1999.
5. J. Gu, F. Zhou, W. Xie, S. C. Tam, and Y. L. Lam, " Passive Q-Switching of a diode-pumped Nd:YAG laser with a GaAs output coupler" ,*Opt. Commun*., **165**, pp. 245-249, 1999.
6. J. Gu, F. Zhou, S. C. Tam, W. Xie, Y. L. Lam, C. H. Kam, W. Xie, T. K. Lim, and K. T. Wan, "Q-Switching of a diode-end-pumped Nd YVO_4 laser with GaAs output coupler" . Int. Sym. on Photonics and application, Paper No SPIE 3898-15, Nov. 29—Dec. 3, 1999. Singapore.
7. J. Gu, F. Zhou, S. C. Tam, Y. L. Lam, C. H. Kam, T. K. Lim, K. T. Wan, and W. Xie, "Q-switched diode-end-pumped Nd:YVO_4 laser providing 2.2 ns-pulse with GaAs output coupler" . Submitted.
8. V. Swaminathan and A. T. Macrander, *Materials Aspects of GaAs and InP Based Structures*, Prentice, New Jersey, 1990.
9. R. K. Willardson and E. R. Weber, *Nonlinear Optics in Semiconductors I: Semiconductors and semimetals*, Chap. 1, Academic Press, San Diego, 1999.