HIGH POWER CONTINUOUS-WAVE 1064 NM DPSS LASER FOR MACHINING SEMICONDUCTOR AND METAL MATERIALS

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ABSTRACT: *A diode-pumped solid-state (DPSSL) laser system with 808 nm laser as pump source has been developed successfully. We used the optically anisotropic crystal* $Nd:YVO_4$ *as the active medium. The threshold pump power and slope efficiency were measured and discussed. With lowly doped crystal* $Nd:YVO_4$ *0.27% and concave-plane cavity, the laser showed good performance in the pumping range up to 11 W. Using the 1064 nm beam, micromachining were successfully conducted upon some normal materials such as plastic, wood; some semiconductors such as silicon and metals such as aluminum, copper, steel.*

Keywords: *Nd:YAG,* $Nd:YVO_4$*, DPSSL, threshold power, slope efficiency.*

1. INTRODUCTION

In the late 1980s, laser diode at 808 nm with reasonable price made its first debut on the market and many scientists turned their attention to it in searching for an alternative pump source for Nd:YAG (yttrium aluminum garnet doped with neodymium) and other Nd-hosted laser. Previously, the main pump source for Nd:YAG laser and his relatives were flash lamp. Flash lamp spectrum is broad, while 808 nm laser diode spectrum is much narrower, so the Nd-hosted crystal absorbs most of the power of the laser diode. In addition to that, diode-pumped Nd: hosted laser has many advantages over flash lamp-pumped Nd:hosted laser such as lifetime and compactness. The reason to use 808 nm laser to create 1064 nm laser is the beam quality: 808 nm laser is very powerful, yet its beam quality (especially divergence) ranks as the worst in all laser types.

Since the appearance of this new pump source and the advancing achievements in crystal growth technology, a series of new active medium has been developed: $Nd:YVO_4$, $Nd:GdVO_4$ and Nd:glass, among which $Nd:YVO_4$ (yttrium orthovanadate doped with neodymium) is the most interesting material. This material has absorption cross section at 808 nm and emission cross section at 1064 nm much greater than that of Nd:YAG [1]. This makes the $Nd:YVO_4$ laser has a much lower lasing threshold than Nd:YAG laser. However, the thermal conductive coefficient of $Nd:YVO_4$ is smaller than that of Nd:YAG, thus heat management for $Nd:YVO_4$ is more difficult. Therefore, Nd:YAG laser has been being replaced by $Nd:YVO_4$ laser in only low and medium output power modules.

The temperature of 808 nm pump laser diode is also very important. The p-n junction, which emits 808 nm beam when injected with electrical current, also emits an amount of heat equal to approximately 50% of the input electrical power. High temperature at the laser diode does not only shorten the life of the laser, but in case of excessively high temperature, can even result in instant death of the laser diode.

Active medium temperate also needs decent concern. When absorbing 808 nm beam from the pump laser diode, $Nd:YVO_4$ use part of it to generate 1064 nm (and then 532 nm) beam, the rest absorbed pump power wastes as heat inside the crystal. The crystal may fracture under steep temperature gradient [2], and the 532 nm output also decreases. Below the fracture limit, temperature gradient still causes bad effect, among which thermal lens [3] is the most annoying. Doping concentration plays very important role in $Nd:YVO_4$ laser [4] due to the low thermal conductivity of $Nd:YVO_4$.

In this work, a laser pumped by 808nm laser diode was constructed. The laser operated in continuous wave (CW) mode. The active medium investigated was $Nd:YVO_4$ crystals. Threshold power and slope efficiency were measured and compared. The output 1064 nm beam was tested on plastic, wood, paper; semiconductors such as amorphous silicon and crystalline silicon wafer; metals such as aluminum, copper and steel.

2. OPERATION OF 1064 NM DPSS LASER

2.1 Effect of laser cavity configuration

Laser cavity can be of plane-plane, concave-plane, concave-concave, concave-convex… forms. Each configuration has different stability, efficiency, compactness and other characteristics. One has to base on the application requirements to choose the suitable configuration.

In this study, we use two kinds of configuration: plane-plane and concave-plane. The former cavity is very compact yet its efficiency is not as good as the latter. Further details are in the result and discussion section.

2.2. Effects of laser cavity parameters

Mirror's radius of curvature, cavity length, position of the $Nd:YVO_4$ crystal within the cavity all affect, more or less, the performance of the laser. The effects do not limit only to the power of the 1064 nm beam, but also many other features. In this paper, we study the effect of cavity length on the threshold pump power (the minimum power of 808 nm beam pumped required for the laser to start emit 1064 nm beam) and slope efficiency (the slope of the input-output line).

The cavity stability [2] is characterized by the G parameter which must satisfy the inequality (2):

(1) $$G = \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right)$$

(2) $$0 \le G \le 1$$

Where L (mm) is the cavity length (distance between two mirrors), R_1 and R_2 are radii of curvature of mirror 1 and 2, respectively. Cavity with G = 0.5 has good stability (diffraction loss in the cavity is rather small, so with a low pump power the cavity can emit great amount of laser beam); while cavity with G < 0 or G > 1 is unstable (diffraction loss becomes so severe that the cavity can not emit any laser beam at any level of pump power). Cavities with G =0 or 1 is on the edge of stability, they may emit laser beam, but only at high pump power, and with slight vibration or shock the cavity may cease to emit laser beam completely.

The plane-plane cavity has infinite R_1 and R_2, naturally it does not satisfy the inequality (2) and can not emit any 1064 nm beam at all. However, in our experiment, it still emits. We will discuss this anomaly in the result and discussion section. For the concave-plane cavity in our study, R_2 is infinite, so the stability condition can be expressed as:

(3) $0 < L < R_1$

Where R_1 is the curvature of the concave mirror.

From (3) we can see that, theoretically, the laser system start can not emit any 1064 nm beam at all when the cavity length exceeds R_1. However, in our experiment, the cavity went unstable and ceased emitting 1064 nm when the cavity length is 112 mm. This will also be presented and discussed our paper.

Inside the laser cavity, the 1064 nm beam forms a standing wave. Its fundamental transverse mode varies as described in Figure 1.

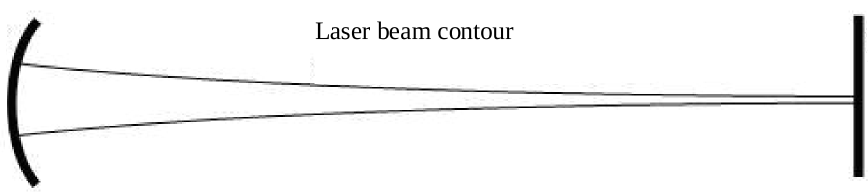


Figure 1. Fundamental transverse mode of 1064 nm beam inside the concave-plane cavity

The distance between the beam waist (the location where the diameter of the laser beam is smallest) to mirror 2 is given by [5]:

(4) $$L_2 = \frac{L(R_1 - L)}{(R_1 + R_2 - 2L)}$$

In concave-plane cavity, $R_2 = \infty$ so:

(5) $L_2 = 0$

Which mean the 1064 nm beam waist lies right on the plane mirror. On the other mirror (mirror 1) it has the diameter [2]:

(6)

$$\omega_1^4 = \left(\frac{\lambda R_1}{\pi}\right)^2 \frac{(R_2 - L)}{(R_1 - L)} \frac{L}{(R_1 + R_2 - L)}$$

Again, in concave-plane cavity, $R_2 = \infty$ so:

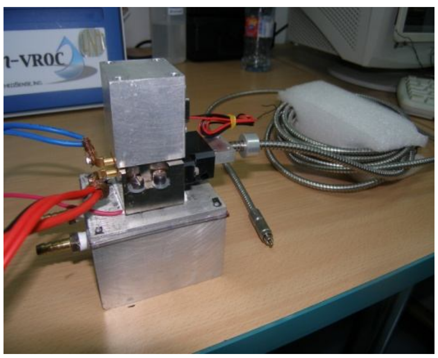
(7) $$\omega_1^4 = \left(\frac{\lambda R_1}{\pi}\right)^2 \frac{L}{(R_1 - L)}$$

From equations (5) and (7) and the laser beam contour in *Figure 1*, we can see the beam has its waist on plane mirror and then it diverges with position nearer to concave mirror.

Through (7), we can see that when the cavity length increases from 0 to R_1, the beam diameter on concave mirror increases from 0 to infinitive. According to D.G. Hall [6], to achieve high efficiency, the smaller the ratio ω_p / ω_l (where ω_p, ω_l are the waists of the 808 nm pumping beam and 1064 nm lasing beam, respectively) the better. Because the waist of 808 nm pumping beam in this experiment is kept constant, we expected that longer cavity would have lower ratio ω_p / ω_l and thus give higher power of 1064 nm beam, and when L is approximately to R_1 we will achieve the highest output power. However, the fact is in the opposite.

3. EXPERIMENT

In our setup, we used a 808 nm laser diode (capable of emitting 20 W beam power) from Spectra Physics,USA to pump the crystal.



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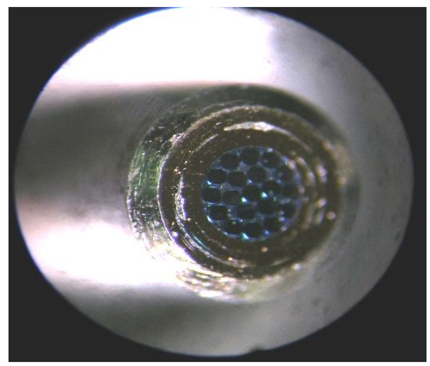


b

Figure 2. Fiber-coupled laser diode (a) and the output bundle tip under microscope (b). Note the 19 fibers arranged into a round tip in (b)

The laser diode beam was coupled in a bundle of 19 fibers, whose total core diameter is 1100 μm, and imaged into the crystal through a lens system which has the imaging ratio 1.6:1. The waist of 808 nm beam inside Nd:YVO_4 crystal is therefore 687.5 μm.

In the setup of plane-plane cavity (Figure 3), the active medium was Nd:YVO_4 doped 1% (3×3×2 mm). The crystal is coated high reflection (HR) thin films at 1064 nm on face S_1 and antireflection (AR) thin films at 1064/808 nm on face S_2. Face S_1 and the mirror 4 form a plane-plane cavity.

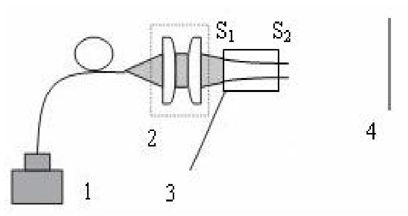


Figure 3. Setup of the laser system with plane-plane cavity. 1: Diode laser; 2: coupling lenses; 3: $Nd:YVO_4$; 4: output mirror

In the setup of concave-plane cavity (Figure 4), the active medium were $Nd:YVO_4$ doped 0.27% (3×3×12 mm). The crystal is coated antireflection (AR) thin films 1064/808 on both sides. The concave mirror is coated HR1064 and radius of curvature 100 mm. The plane mirror is coated with transmission T=20% at 1064 nm The concave face of mirror 3and the plane mirror 5 form a concave-plane cavity.

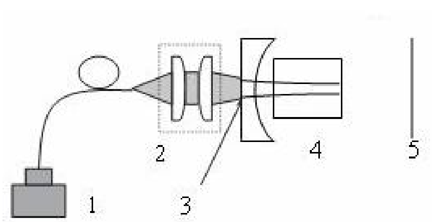


Figure 4. Setup of the laser system with concave-plane cavity. 1: Diode laser; 2: coupling lenses; 3: Input mirror M_1; 4: $Nd:YVO_4$; 5: output mirror

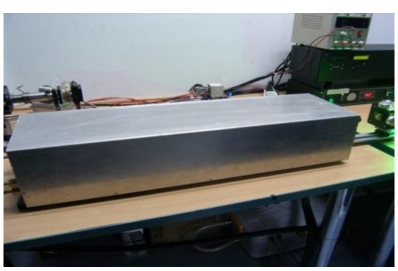


Figure 5. The laser packaged into box and is used in second harmonic generation experiment at LNT.

A 808 nm filter was used to cut all residual 808 nm beam from the 1064 nm output beam. The crystals, mirrors and filters are all from Casix, China.

The power of 1064 nm output beam was measured with the integrated sphere S142C and power meter PM100D from Thorlabs, USA

The laser beam was used to etch and cut several materials including wood, plastic; aluminum, copper, steel and silicon wafer. The etching geometries were inspected with metallurgical microscope GX51 (Olympus, Japan) and Scanning Electron Microscope JSM-6480LV (Jeol Inc, Japan) at LNT.

4. RESULT AND DISCUSSION

4.1. Performance of the lasers

The laser system with plane-plane cavity started to emit 1064 nm beam when the power of the pumping 808 nm beam exceeded 1.26 W. Figure 6 is the graph of 1064 nm beam versus 808 nm beam (cavity length L= 50 mm). At 11.26 W of 808 nm beam, a maximum 2.8 W of 1064 nm beam was collected.

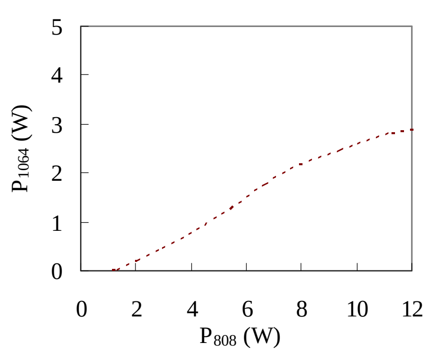


Figure 6. Output versus input of plane-plane cavity, L =50

Why the plane-plane cavity can be capable of emitting 1064 nm, while conditions (1) and (2) state that is impossible? The reason may be the thermal lens in Nd:YVO_4: part of 808 nm beam absorbed by Nd^{3+} ion in YAG lattice does not help generate 1064 nm beam, but wastes as heat. This heat creates a temperature gradient in Nd:YVO_4 and thus a gradient of refractive index. Medium with refractive index gradient bends light that propagates through it, thus acts as a lens. The G parameter of a cavity with internal lens is:

$$(8)\ G = \left(1 - \frac{L_2}{f} - \frac{L}{R_1}\right)\left(1 - \frac{L_1}{f} - \frac{L}{R_2}\right)$$

With R_1, R_2 equal to infinitive, the condition (2) now becomes:

$$(9)\ 0 \le \left(1 - \frac{L_2}{f}\right)\left(1 - \frac{L_1}{f}\right) \le 1$$

Thus the thermal lens inside Nd:YVO_4 somewhat stabilizes the cavity. However, this cavity was still rather vulnerable to vibration: small vibration caused the laser output drop drastically, and sometimes disappear completely.

Table 1 lists the power of 1064 nm beam at 6.64 and 11.26 W of 808 nm pump power, with various cavity lengths. Through the table, one can see that shorter cavity has higher efficiency.

From Figure 6, we can see the graph is linear in the pumping range from 0 to around 7 W, this is the good working range of this laser, after that there is a drop in slope efficiency. Pumping more 808 nm beam caused our crystal to crack and become permanently useless. This is due to the high doping concentration of Nd^{3+}. In laser with Nd:YVO_4 0.27%, this phenomenon did not occur.

In the good working range, the relation between input-output in this plane-plane cavity can be expressed with the equation (10):

$$(10)\ P_{1064} = 26\%\left(P_{808} - 1.26\right)$$

Where P_{808} and P_{1064} are power of input and output beam, in Watt(s), 26% is the slope efficiency, and 1.26 W is the threshold power.

Table 1. Output at P808 = 6.64 and 11.26 W from plane-plane cavity

L (mm)	P_{1064} at P_{808}=6.64 W	P_{1064} at P_{808}=11.26 W
10	2.02	3.71
13	2.05	3.67
20	1.87	3.68
35	1.93	3.56
40	1.93	3.35
45	1.88	3.19
50	1.74	2.8
70	1.79	2.85

Figure 7a andFigure 7b shows the graph of input versus output in concave-plane cavity. The first thing to remark is the stability with respect to cavity length. As stated in (3), cavity with L longer than 100 mm (value of R_1) can not emit laser beam. However, from the graph, we can see that at even L=100 mm, the cavity still emitted 1064 nm beam, and from the data collected we see that the 112 mm long cavity still emitted 10 mW of 1064 nm when pumped at 11.26 W. This, once again, can be the effect of thermal lens said above.

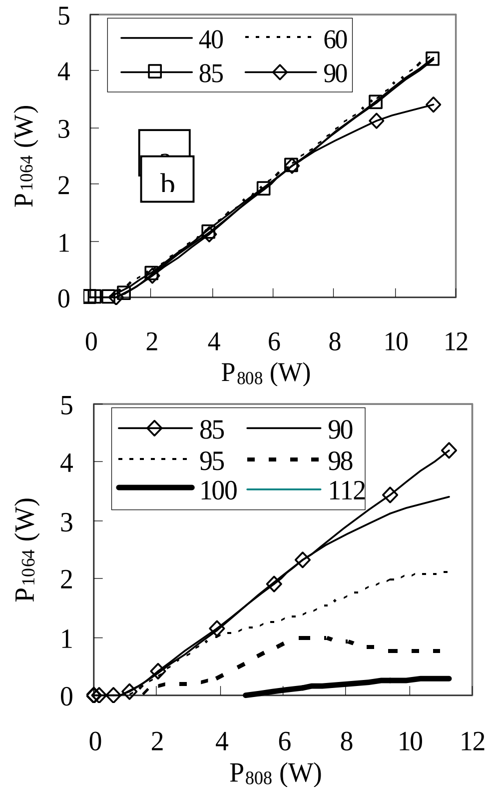


Figure 7. Output versus input of concave-plane cavity

We can also see that cavities with length from 40 to 85 mm are nearly identical to each other, and show complete linearity over the pumping range. Maximum output of 1064 nm

Table 2lists the threshold powers P_{th} of concave-plane cavity at different cavity length.

was achieved with the 60 mm long cavity (approximately 4.3 W of 1064 nm beam when pumped at 11.26 W of 808 nm beam). Fitting the real data with the least square method, we received the values of fitted threshold power and fitted slope efficiency. The slopes of the lines are approximately 37 % and the threshold power (the minimum power of 808 nm beam pumped required for the laser to start emit 1064 nm beam) is 0.49 W. Therefore, the input-output relation can be expressed with the expression (11):

$$(11)\ P_{1064} = 37\%\left(P_{808} - 0.49\right)$$

With cavity length longer than 85 mm, the laser began to show degradation, and sometimes plus chaos, in slope efficiency. The effect became more apparent with longer cavity. The 98 mm long cavity showed very chaotic slope. In addition, threshold became larger.

Table 2. Threshold power of concave-plane cavity

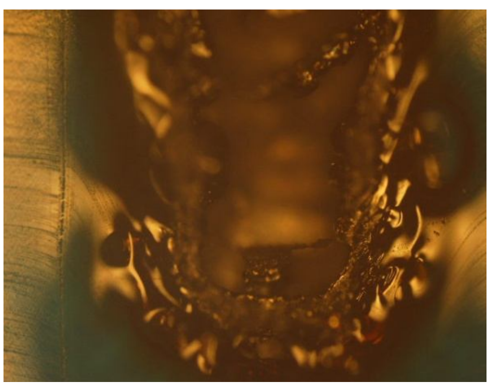
L (mm)	40	53	60	85	90	95	98	100	112
P_{th} (W)	0.51	0.48	0.49	0.50	0.83	1.11	2.03	4.8	11

As we mentioned in the previous part, Hall D. G. stated that the smaller the ratio ω_p / ω_l (where ω_p, ω_l are the waists of the 808 nm pumping beam and 1064 nm lasing beam, respectively) the better for efficiency. The Nd:YVO_4 crystal is placed very close to the concave mirror, because the 808 nm beam waist right there, and we can from the equation (7) see that cavity with longer length has larger beam diameter on concave mirror, thus a lower ω_p / ω_l. On the contrary, the G parameter approaches unity when L approaches the value of R_1, the cavity stability decrease with longer cavity. These two opposite trends lead to a compromise: a L value to balance between the ω_p, ω_l ratio and the G parameter. That is why the 60 mm long cavity showed the best performance.

From the results, we can see that plane-plane cavity with Nd:YVO_4 1% can be used to produce compact laser (the cavity length can goes down to 10 mm). However, in terms of output 1064 nm beam power and electrical saving, concave-plane cavity with Nd:YVO_4 0.27% is the better choice: with the same amount of electrical power driven into the 808 nm laser diode, one can acquire more powerful 1064 nm beam from concave-plane Nd:YVO_4 0.27% laser.

In practical usage, we also notice the concave-plane cavity is much more resistant to vibration than the plane-plane cavity. Strong vibration may make the former power's output drop, but only in small amount. In no experience have we ever seen the 1064 nm beam disappeared completely due to strong vibration. Test on misalignment sensitivity needs to be carried out to quantitatively determine the reliability of this laser in harsh working conditions (against shock and/or vibration). This laser, however, is promising in practical usage and commercial production.

4.2. Investigation in application



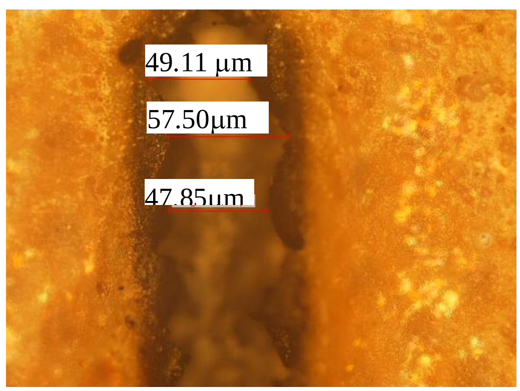


Figure 8. Etched groove on plastic sheet (a) and on wood sheet (b) under metallurgical microscope

The 1064 nm beam was tested on several materials and is capable of cutting through plastic and wood. Figure 8 shows etched grooves on plastic and wood. For aluminum and copper in thin layer form, the laser beam can also etch, and the etching threshold (minimum power of 1064 nm beam to etch) is about 0.5 W. However, etching capability on bulk aluminum and copper is very weak.

Figure 9. Photograph of cut-through hole on 100 μm steel plate (b)

For steel, the threshold power for etching is not high: about 2 W. The low threshold for etching steel may be due to low thermal conductivity of steel compared to silicon: 18 $W/m^{-1}K^{-1}$ versus 130 $W/m^{-1}K^{-1}$. Etching steel by 1064 nm beam is much easier than etching silicon, to the degree that there was spark during etching (the steel particles being burnt with atmospheric oxygen), and after 5 minutes of etching a circle groove at the same position on the steel plate, we can cut through and create a hole, as in Figure 9.

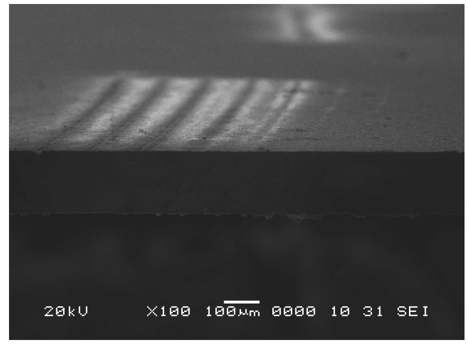


Figure 10. SEM images of etched groove on 200 μm thick silicon wafer

Figure 10is the SEM images of 11 etched grooves on 200 μm thick silicon wafer under different power of 1064 nm beam. The lens used to concentrate the beam power has the focal length 50 mm. From left to right, the powers of the 1064 nm beam are 5 W, 5 W, 5 W, 3.86 W, 3 W, 2.3 W, 1.45 W, 0.75 W, 0.56 W and 0.37 W. We can see only the first six grooves through SEM image, thus the etching threshold for this material is 2.3 W. The existence of this high threshold originates from the local temperature reached. The local temperature is decided by the heat per unit volume of silicon generated when silicon absorbs the 1064 nm and the heat dissipated to the surrounding area. Silicon has higher thermal conductivity than that of wood, plastic, thus a more powerful beam is required to make the local temperature reaching burning point.

In this study, we have not yet perform test with lens of other focal length. The etching threshold when using lens of shorter focal length is expected to be lower and vice versa.

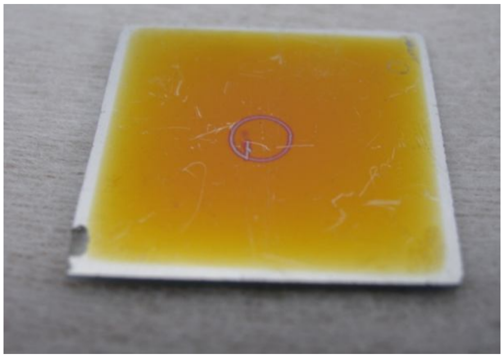


Figure 11. Photograph of etched circle on amorphous silicon deposited on glass

Amorphous silicon deposited on glass substrate is rather easy to etch: 0.5 W of 1064 nm beam can easy etch a circle on it, as seen in Figure 11.

Of course, many material properties contribute to the burning under laser beam: specific heat capacity, reflectance and absorbance at 1064 nm, thermal conductivity, combustion with oxygen [7]. A decent modeling is necessary to optimize micromachining. In our study, we mainly base on experiment to determine the threshold power.

5. CONCLUSION

We have successfully developed high power 1064 nm operating in CW mode with Nd:YVO_4 as active medium. The laser performance is stable within pumping range from 0 to 11 W. The maximum output power is 4.3 W. The Nd:YVO_4 laser with concave-plane cavity is more cumbersome than Nd:YVO_4 1% laser with plane-plane cavity, but the former showed superiority in terms of threshold pump power and slope efficiency. The laser beam can etch many kind of materials, but is most applicable to wood, plastic sheet, steel plate and silicon wafer.

LAZE DPSS PHÁT LIÊN TỤC CÔNG SUẤT CAO BƯỚC SÓNG 1064 NM ỨNG DỤNG CHO GIA CÔNG BÁN DẪN VÀ KIM LOẠI

Phan Thanh Nhật Khoa, Đặng Mậu Chiến

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TÓM TẮT: *Một laze rắn bơm bằng laze bán dẫn (DPSSL) sử dụng laze bán dẫn bước sóng 808 nm làm nguồn bơm đã được xây dựng thành công. Chúng tôi sử dụng tinh thể bất đẳng hướng quang học Nd:YVO_4 làm môi trường hoạt tính. Ngưỡng phát và độ dốc hiệu suất đã được đo đạc và thảo luận. Với tinh thể có nồng độ pha tạp thấp này (0,27%) và cấu hình hệ cộng hưởng lõm-phẳng, hệ laze tỏ ra hoạt động tốt khi được bơm đến 11 W. Chùm laze 1064 nm đã được đem thử nghiệm vi gia công thành công trên một số vật liệu thông thường như nhựa, gỗ; bán dẫn như silicon; kim loại như nhôm, đồng và thép.*

Từ khóa: *Nd:YAG, Nd:YVO_4, DPSSL, ngưỡng phát, độ dốc hiệu suất*

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