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Diode pumped Q-switched Nd:YAG laser at 1064 nm with nearly diffraction limited output beam for precise micromachining of natural diamond for micro electro mechanical systems (MEMS) applications

S. K. SUDHEER*, V. P. MAHADEVAN PILLAI, V. U. NAYAR
Department of Optoelectronics, University of Kerala, Kariavattom, Thiruvananthapuram-695581, Kerala, India

In the present investigation, a diode pumped Q-switched Nd:YAG laser is used to study the various aspects of natural gem quality natural diamond processing for MEMS applications. The experimental setup consists of a diode pumped Q-Switched Nd:YAG laser capable of operating at wavelength 1064 nm. The diamond cutting is performed by making the “V” shaped groove with various opening angle. The variation of weight loss of diamond during cutting are noted for both lamp pumped Nd:YAG laser as well as for diode pumped Nd:YAG laser. The cut surface morphology, elemental and structural analysis of graphite formed during processing in both the cases are compared using EDAX and XRD techniques. The diode pumped Q-Switched Nd:YAG laser have shown very good performance in terms of peak to peak out put stability, minimal spot diameter, smaller divergence angle, higher peak power in Q-Switched mode and good fundamental TEM_{00} mode quality for processing natural diamond stones. Less weight loss, less micro cracking and good surface quality of diamonds are achieved in this case.

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1. Introduction

Diamond is mechanically one of the strongest materials known and has very high dielectric strength. Single crystal natural diamond is generally recognized as a principal candidate for next generation semiconductor materials. The above properties are all related to the strength of the carbon bonds in the crystal and its structure. Major advantages for the use of diamond technology for applications such as microelectronic devices, sensors, micro electromechanical systems, and high power devices are its superior electronic properties at much higher temperatures and harsh environments such as high breakdown voltage, electron saturation velocity, carrier mobility, thermal conductivity, and electrical stability [1-4]. Electrical devices based on wide-band gap (WBG) semiconductors such as diamond allow operation at high frequencies and temperatures. Energies of 13eV to 16eV are required to create electron-hole pairs in it. The band-to-defect recombination mechanism dominates, and a carrier lifetime of a few hundred picoseconds makes the diffusion length less than a micron. Natural diamond and CVD diamond have been used in radiation detector applications. Their high carrier mobilities and carrier velocities provide quick response times, and, for a given radiation energy, the current resulting in diamond will be smaller than that resulting in a detector made with silicon or germanium allowing it to withstand higher energy radiation without permanent damage. Diamond's dielectric strength, depending on the quality of the material, is in the MV/cm range [5]. In optoelectronics, the use of WBG materials for applications such as LEDs and UV-sensors enables working in the UV range of the light spectrum. Therefore WBG materials are intensively studied nowadays for novel applications in devices physics. Diamond has a very privileged position between the wide-band gap materials due to its extreme properties. It can for example be used for devices working at temperatures as high as 600 °C and at high powers and voltages.

The impact of laser technology in the diamond industry has revolutionized the field in many respects [6-9]. There are many advantages for diode pumped Nd:YAG laser processing of diamonds for producing nearly flawless single crystal diamond wafers and crystals for the above mentioned applications. Diode pumped lasers are able to saw complex crystals and improve yields. They provide lower breakage rates even for sensitive diamonds and lower weight loss for difficult stones. For cutting natural diamonds, the vaporization cutting technique using Nd:YAG laser with intensity range 10^6-10^7 W/cm [10]. In this scheme, the focused laser beam heats up the surface to the boiling point and generates a keyhole. The keyhole causes a sudden increase in absorptivity due to multiple reflections and hole deepens quickly. As it deepens, vapor is generated and escapes blowing ejecta out of the kerf and stabilizing the molten walls of the hole [11,12].

Micro Electro Mechanical Systems (MEMS) are very small mechanisms. Such devices can be a wide variety of different mechanisms, such as fluid channels, gears, tweezers, Optical Circuits and mirrors. Even though almost all MEMS devices look very complex and difficult to build, the manufacturing process is aided by the increasingly developed laser machining techniques. This method uses a focused beam of laser light which will blast away unwanted portion and create the desired structure [13]. Issues such as ablation threshold, ablation rate, incubation of damage at subthreshold fluences, edge resolution, debris creation and residual substrate damage are all important in determining the suitability of this technique for these applications [14-19]. In the present investigation a diode double end pumped Nd:YAG laser is characterized using planar resonator with a resonator length of 700 mm with 20% output coupling for the processing of ultra hard materials such as natural diamond for fabricating MEMS devices.

2. Experimental

In the present investigation, a diode pumped Nd:YAG Q-switched laser and lamp pumped Nd:YAG laser-both operating at 1064 nm have been employed for the processing of single crystal natural diamonds to study the various aspects of processing and the relative merits and demerits. The weight loss of diamond and formation of micro cracking during processing have studied for the above two cases. The characteristics of graphite formed during processing, elemental analysis, surface morphology of cut face and process dynamics have been studied using EDAX and XRD techniques. The experimental set up used for laser cutting of diamond is shown in Fig. 1.

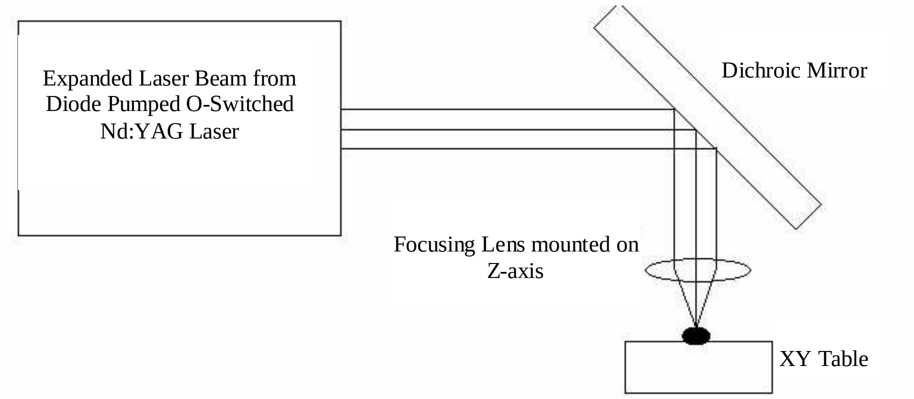


Fig. 1. Experimental Setup for laser processing of diamond using diode pumped Nd:YAG laser at 1064 nm.

The experimental setup consists of the diode pumped and lamp pumped Nd:YAG lasers arranged in the above configuration for cutting diamonds .In order to reduce the beam divergence, the laser beam is expanded using a beam expander with expansion ratio 1:8. The expanded beam is reflected by an angle of 90^o by a beam bender or dichroic mirror placed at 45^o. The laser beam after bending is focused by a multi-element focusing lens onto the diamond sample so that the focused spot size is ~35 μm in the case of lamp pumped Nd:YAG laser where as it is ~10 micron in the case of diode pumped Nd:YAG laser due to lower beam quality factor (M^2 parameter). The diamond sample is fixed over the CNC table which is capable of moving in XY co-ordinate axes as per program. The diode pumped and lamp pumped Nd:YAG lasers at 1064 nm are operated in the Q-Switched mode at a repetition rate of 10 KHz and at average power of 6 W. For values of Q-Switch frequency above these and for value of average power below these, the machining is found not proper. The thickness of diamond to be sawn will be given as input and hence the angle of cut was determined by the cutting software.

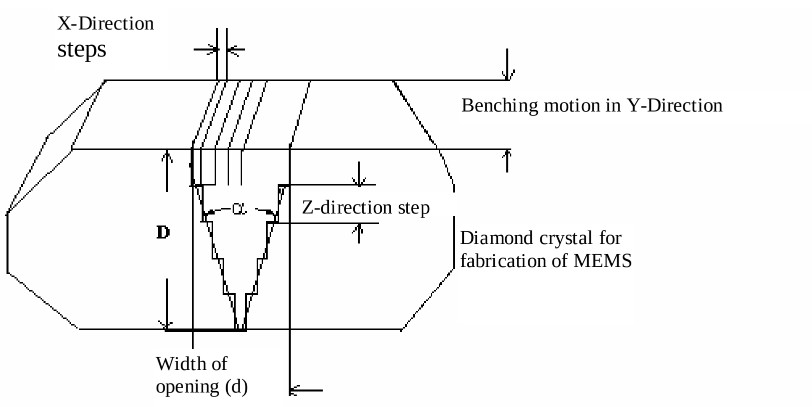


Fig. 2. Laser cutting geometry of natural diamond crystal using diode pumped Nd:YAG laser for MEMS applications.

As per the cutting profile shown in Fig. 2, the opening angle α is given by

$$\alpha = 2\tan^{-1}\left(\frac{d}{2D}\right) \tag{1}$$

where d is the width of opening and D is the depth of cutting. The aspect ratio of cutting is defined as ρ and is given by

$$\rho = \frac{D}{d} \tag{2}$$

A parameter called weight loss parameter W is defined and is given by

$$W = \tan\left(\frac{\alpha}{2}\right) \tag{3}$$

The weight loss of diamond during cutting is found proportional to the weight loss parameter W and hence opening angle α.

The diamonds are weighed before and after laser cutting. Each diamond is marked with black ink to indicate the sawing plane and tightly glued into a metallic pot. The pot with diamond is placed in the fixture placed tightly over the XY table. The diamond is sawn perfectly. The two pieces are weighed again to find out the weight loss. From the value of weight loss, percentage of weight loss is calculated in the case ablation with both diode pumped and lamp pumped Nd:YAG lasers. The presence of micro cracking is observed in two cut pieces of each diamond. The elemental and structural analysis is studied using EDAX and X-Ray diffraction (XRD) studies.

3. Results and discussion

The various results are explained here. The variation of percentage of weight loss of gem quality diamond with its weight during processing with both diode pumped and lamp pumped Q-switched Nd:YAG lasers at 1064 nm is given in Fig. 3.

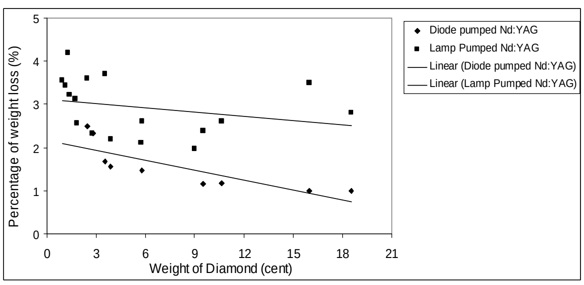


Fig. 3. Variation of percentage of weight loss of gem quality diamond with its weight during processing with diode pumped and lamp pumped Q-switched Nd:YAG lasers at 1064 nm.

It is observed that the percentage of weight loss is decreasing with weight of diamond processed in the case of cutting with diode pumped Nd:YAG laser. Regarding the formation of micro cracking which is considered as the most serious problem in laser processing of diamond, no micro cracking is observed. This indicates that processing of natural diamonds using diode pumped Nd:YAG laser is almost risk free. This may be due to extremely good TEM_{00} beam quality and output power stability. But in the case of lamp pumped Nd:YAG lasers, due to the higher output power instability and fluctuations can cause process induced Process-induced Gletzes (PIGs). Stress–induced Gletzes (SIGs) only occur in highly stressed stones. They occur no matter what tools are used for cutting the stone. PIGs are breaks which are unique to the laser. If one had sawn the stone by a different technique, it would not have broken. The main causes of PIGs are high power settings, lack of peak pulse suppression of the Q-switching of the laser, a poorly designed focusing system, poor operational techniques or high output power instability and pulse-to-pulse instability. As highly incoherent arc lamp is the pump source in this case there are some upper limits for these instabilities below which it is technically difficult to attain good output power and pulse-to-pulse stability. Energy Dispersive Analysis using X-Rays (EDAX) patterns in Figs. 4(a) and 4(b) indicate the formation of graphite in both the cases of ablation using diode pumped as well as lamp pumped Nd:YAG lasers.

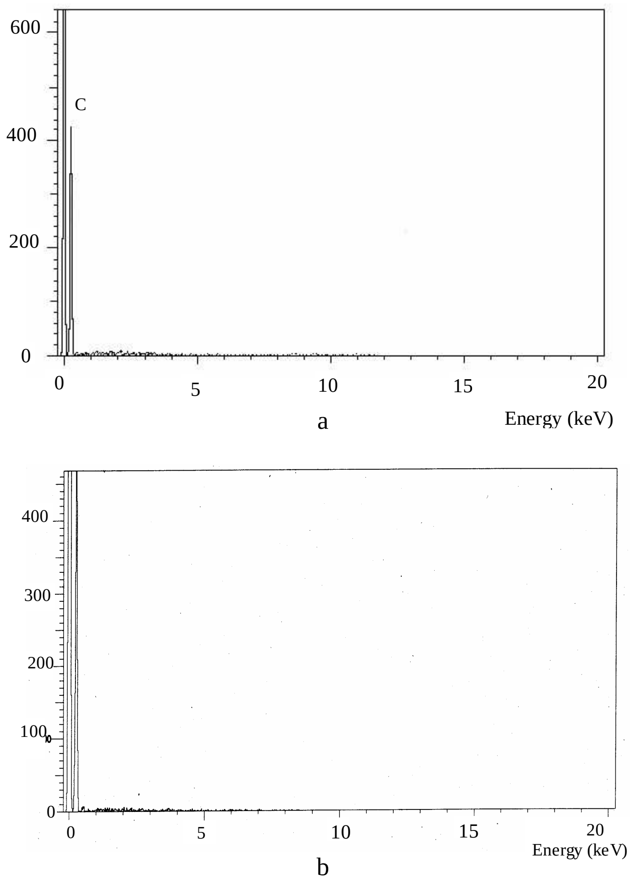
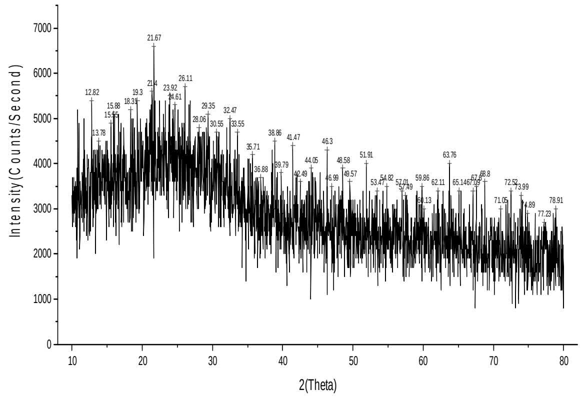
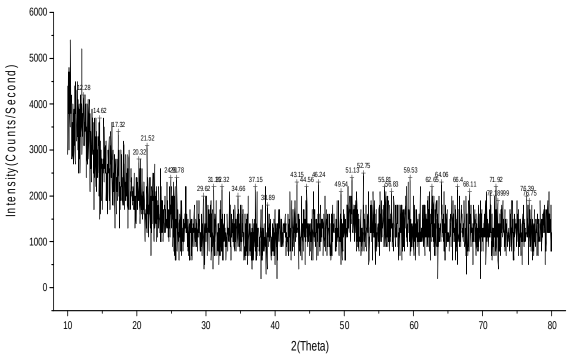


Fig. 4. (a) Energy Dispersive Analysis using X-rays (EDAX) patterns of cut surface of natural diamond using lamp pumped Q-Switched Nd:YAG Laser (b) using diode pumped Q-Switched Nd:YAG Laser at 10 KHz.



a



b

Fig. 5. (a) XRD patterns of laser cut surface of natural diamond using lamp pumped Q-Switched Nd:YAG Laser (b) using diode pumped Q-Switched Nd:YAG Laser at 10 KHz.The XRD pattern in Figs. 5(a) do not indicate any serious structural changes of lattice due to laser processing at very high peak power densities.

4. Conclusion

We have described the processing of natural diamond crystals using an efficient, diode double end pumped high-gain Nd:YAG laser that produces Q-switched pulses with very good TEM_{00} beam quality and low M^2 parameter (<1.1). The processing using this high peak power, high brightness laser source results in excellent surface quality of cut surface with almost complete absence of Heat Affected Zone and presence of graphite which makes DPSSL ideal for fabricating diamond based MEMS devices. This may be due to the high peak power density due to lower value of M^2 parameter in case of former. The fine surface quality reduces the post processing of diamond substrates.

The diode pumped Q-Switched Nd:YAG laser system have shown very good performance in terms of peak to peak out put stability, minimal spot diameter, smaller divergence angle, higher output power in both CW and Q-Switched modes and good fundamental TEM_{00} mode quality. The energy density at the diamond work piece is found out at two different focusing lenses. In both the cases it is showing a linear variation with laser output power. The weight loss analysis shows that the present system is showing smaller weight loss compared to conventional lamp pumped laser cutting systems.

Similar to the case of lamp pumped Nd:YAG lasers, the main steps involved during the diode pumped Nd:YAG laser processing of diamond are absorption of radiation, heating of diamond sample, melting and vaporization, ablation and material removal. As the spot size is still smaller in the case of DPSSL the process rate is fast. In the initial stage the absorption of laser radiation by the diamond sample is taking place. The absorption process comprises of two parts. They are nonlinear optical absorption (multi photon absorption) and linear absorption. There are chances of multi-photon processes in the absorption of laser radiation by diamond because of its wide band gap. Thus multi-photon process are required for the excitation of electrons. As diamond has a band gap of 5.47 eV, 5-photon processes are needed at 1064 nm, 3-photon processes at 532 nm and 2-photon processes at 266 nm for initial excitation of electrons. It can be assumed that the absorption of energy by the free carriers that are produced in the initial stages of pulse plays an important role in the overall energy deposition. It means that even though nonlinear absorption across the band gap is necessary for the production of free carriers, later on the linear absorption of energy by the free carriers becomes dominant.

It is already mentioned that the cutting line is marked by black ink so as to enhance initial absorption which is not sufficient. In order to modify the diamond substrate, one need strong electronic excitations in diamond. In the nanosecond time regime, the laser ablation of diamond is disturbed with the undesirable thermal effects which drastically reduces the cutting efficiency. To our expectation, an important reason why laser pulses in the nanosecond range cause more undesirable material damage is the fact that there are processes competing with the laser excitation in the target region, namely the diffusion of hot carriers and heat conduction. These processes carry the energy and thus the damage far into the material while cooling down and de-exciting the focus area of the laser. Only if the laser pulse duration is shorter than the typical time scale of the competing processes (which is probably a few picoseconds), it is possible that ablation takes place via non-thermal processes. At the same time, shorter laser pulses also have higher power and thus, multi-photon absorption becomes more likely). From the experimental evidence we have seen, this seems to give much better results in terms of precision material processing. Due to the absorption of laser radiation, the sample gets heated up. In this stage the main problem we encountered was the spreading of heat into unwanted zones inside diamond and hence the increased Heat Affected Zone (HAZ). We identified this as the main reason for breakage problem during cutting using lamp pumped Nd:YAG lasers. The temporal characteristics of laser pulses are optimized to solve this problem to greater extent using diode pumped Nd:YAG lasers.

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* Corresponding author: sudheersk@yahoo.com