Design and Construction of a pulsed Nd:YAG laser for LIBS applications

A Garcia-Villarreal\textsuperscript{1} H Sobral\textsuperscript{2}
\textsuperscript{1}Departamento de Ciencias Básicas, Universidad Autónoma Metropolitana, Av. San Pablo180, Azcapotzalco, 02200 México D.F., México
\textsuperscript{2}Centro de Ciencias Aplicadas y Desarrollo Tecnológico, Universidad Nacional Autónoma de México (CCADET-UNAM), Apartado Postal 70-186, México DF, 04510, México.

E-mail: lgvangel@gmail.com

Abstract. A multi-pulse Nd:YAG laser was designed and built, that can be used as an excitation source for Laser Induced Breakdown Spectroscopy (LIBS) experiments. A trigger and a power supply for the flash lamp has been successfully developed. A cooling system that uses a distilled water flow for the active medium was implemented. The laser has an output energy of $306 \pm 7 \, \text{mJ}$ for 1 Hz repetition rate and its temporal profile is multi-pulse with 1 $\mu$s of average separation between them. To validate the system, the output was used as an ablation source of an aluminum target and the emission was investigated by spectroscopy analysis.

1. Introduction

In 1916 Albert Einstein established the theoretical basis for the laser and the maser, using Planck’s black body radiation law and introducing the concept of stimulated emission of radiation [1]. The first laser was built in 1960 by T. H. Maiman in Hughes Research Laboratories. For this purpose, Cr$^{3+}$ impurity ions present in Al$_2$O$_3$ crystal, known as “Ruby”, served as an active medium in this laser. Later, Sorokin, Stevenson, Kaiser and Garret created the first 4 energy level, solid state laser. CaF$_2$ crystals activated by ions of a rare earth element provided the active medium. The next important step was taken by E. Snitzer in 1961 [2] who built the first solid laser doped with Nd$^{3+}$ ions. The Nd$^{3+}$:YAG laser has been widely positioned, not only for its extensive use in scientific applications, but also for its increasing implementation in the medical field, the industry and even in cosmetology.

On the other hand, Laser Induced Breakdown Spectroscopy is an atomic emission spectroscopy (AES) analytical technique where a pulsed laser serves as an excitation, vaporization and atomization source of a sample. For this aim, a pulsed laser produces a plasma inside or onto the material, and the light is collected and spectrally analyzed [3]. Since the plume is produced by focusing of optical radiation, this method presents many advantages over other AES techniques that use alternate devices (such as electrodes and coils). LIBS allow in situ and remotely sample analysis without any target pretreatment. Quantitative and qualitative analysis is accomplished by following the intensities of the spectral lines. Although LIBS has more than 50 years of existence, many works still focus on the fundamentals of plasma physics. A review of LIBS capabilities shows that this method has a detection sensitivity comparable or greater than the one reached with other extended-field techniques.
1. Design and construction of the laser

The Nd:YAG laser basic scheme consists namely of an optical pumping system, an opto-mechanical system (to form the cavity) and a cooling system. To pump the active medium, the electrical conversion efficiency into optical energy is about 3% [1]. Since a significant fraction of this power is converted into heat, a cooling system must be designed, to avoid the warming of the optical pumping elements. Usually, the optical pumping system consists of a xenon or krypton flash lamp. The first one is preferred since it has emission peaks near the Nd:YAG crystal absorption bands. To couple the light from the flash lamp to the active medium a reflective elliptical cavity was implemented [4]. Typically, both, the flash lamp and the active medium have a thin cylindrical shape. Hence, the best coupling between them is achieved by placing both at the focal points of an ellipse.

The power supply for the flash lamp was designed taking in consideration that the laser frequency has to be variable up to 3 Hz and that the minimum energy output should be 100 mJ per pulse. Subsequently, a capacitor charging circuit with a current limiting resistor [1] and an external trigger was incorporated. Figure 1 shows the electrical circuit constructed for excitation of the xenon flash lamp.

![Flash lamp electrical circuit.](image)

The capacitor C1 is charged through a 120:500V AC/200 mA mono-phasic transformer, a full-wave bridge rectifier and a 860 Ω/300 W current limiting resistor R1. With this circuit a 750 VDC output was obtained.

The Pulse Forming Network PFN circuit allows obtaining a critically damped current pulse according to the physical properties or the flash lamp [6]. The right size of figure 1 shows the corresponding circuit of the PFN. The flash lamp has an impedance $23 \, \Omega \cdot A^{1/2}$ and the pulse width was set to 400 µs for an input energy of 31 J. With these values, a critically damped current pulse of 200 A peak is obtained when $C_1 = 110 \, \mu F$ and $L_1 = 161 \, \mu H$. $C_1$ consists of three 330 μF electrolytic capacitors connected in series. $L_1$ was built with an open ferrite core 2.6 cm in length and 1.0 cm in diameter, with a magneto wire of 0.62 mm in diameter turned 62 times around the core.

The trigger circuit is responsible for high voltage pulse generation, required to ionize the flash lamp gas, allowing the subsequent capacitor discharge through this. For low shooting frequency laser operation, a parallel or series external trigger configuration can be used [5]. In this work we implemented an external trigger where the high voltage pulse is directly applied to a thin copper wire wrapped around the flash lamp. Figure 2 shows the external trigger circuit designed for this purpose.

Here, the microcontroller PIC16F84A /20 MHz, was used as a pulse generator. A LCD screen was connected to this device to show the shooting frequency. Afterward, the generated pulses were used to control the SCRs IRF830 and 50RIA120. The BC547_1 and BC547_2 transistors amplify the signal from the microcontroller, and the SCRs are enabled or disabled by the signal. Moreover the SCRs in turn, allow charging and discharging the 1 µF capacitors, $C_3$ and $C_4$. The charging circuit consists of a 400 VDC /100 mA power supply and a 1.5 kΩ /100
The discharge process is carried out through the pulse transformer which generates 12 kV peak per pulse in the secondary winding. A pulse transformer is usually constructed with a ferrite core, due to its compact size. According to the ratio of the desired voltage, the windings on the secondary coil are usually between tens and hundreds of turns, whereas the primary coil has just a few turns [6]. The pulse transformer designed for this laser was assembled using a square ferrite core, with 2 turns of 1.12 mm in diameter of magneto wire for primary winding and 60 turns of 1.60 mm for secondary.

The xenon flash lamp employed has an internal pressure of 470 torr, an arc length of 9.2 cm (between electrodes), and an internal diameter of 0.5 cm. The active medium is a Nd:YAG cylindrical rod of 11.1 cm in length and 0.8 cm in diameter. In addition, one end of the rod has a 99% reflective coating for 1064 nm; thus, only one mirror is needed to form the resonant cavity [7]. This is similar to the setup used in the first ruby laser, where the rod ends were polished to form the resonant cavity [1]. The optical coupling between the flash lamp and the active medium was performed through a ceramic single elliptical cavity. Finally, to avoid the flash lamp heating, a 60 L/hr flow of distilled water (conductivity of $2 \times 10^{-6} \ \Omega^{-1} \cdot \text{m}^{-1}$) was used. Water thermal dissipation mechanism consists of a radiator coupled to a fan.

2. Laser emission characterization and LIBS application
Laser emission from the built system (see Fig. 3a), was measured using a Power Meter (1918-C, from Newport) with a high power head (818P). The measured mean energy output was 306 ± 7 mJ at 1 Hz. Besides, the temporal output profile was obtained using a fast photodiode with a rise time of 1 ns (DET210, from Thorlabs), connected to a 1 GHZ bandwidth oscilloscope (DPO 4104B, from Tektronix). The laser output consists of a train of pulses of about 1 µs with a total duration of 250 µs as shown in Figure 3b.
To investigate the laser output as an excitation source for LIBS experiments, laser emission was focused onto a solid target, using a 100 mm plane-convex lens L1 (see Figure 4). The sample used was a 6463 commercial aluminum plate (Al 98%, Mg 0.8%, Si 0.5%, and other minor components), which had already been tested with a commercial Nd: YAG laser [8]. Ablated craters were found to be about 250 µm in diameter.

The light emitted by the plasma is collected by a quartz optical fiber bundle and directed to a 500 mm spectrometer with 1800 lines/mm diffraction grating (Spectra Pro 2500, from Acton Research). The dispersed light was detected by an intensified CCD (PiMAX 1024x1024, from Princeton Instruments).

To reduce Bremsstrahlung continuum emission and radiative recombination processes [3], light collection was performed 500 ns after laser onset. Camera exposure time was set to 300 µs to acquire the whole light emission. The laser pulses and the diagnostics system were synchronized using a pulse/delay generator (DG535, from Stanford Research).

The collected emission for the spectral window centered at 282 nm is shown in Figure 5. This region has been chosen since it has several transitions corresponding to the main components of the sample. Emission spectrum is equivalent to the one obtained with a commercial nanosecond Q-switch laser [8], although the laser employed has a pulse duration...
two orders of magnitude larger. This could be due to its multi-pulse features, where successive pulses enhance material removal and simultaneously re-excitation of the produced plasma. Subsequently, it is possible to observe ionic and neutral species of aluminum, magnesium and silicon. Furthermore, the ions detected in this spectrum indicate that the generated plasma can reach a temperature of about 10,000 K.

3. Conclusions
A fully operational Nd:YAG laser, with a multi-pulse output was designed, constructed and characterized. The system has a high energy output, enough to induce breakdown in solid materials, and robust enough for portable LIBS applications. Re-excitation phenomena produced by this multi-pulse laser enhance ions and neutral emission, with figures equivalent to the obtained with other high-price commercial Q-switched lasers. The electrical circuits and all the parts used in this work are affordable and inexpensive in most countries. Besides, since this laser can be adapted according to a user requirement, it could be applied in different fields.

4. References
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