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High energy and dual-pulse MOPA laser for selective recovery of non-ferrous metals

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Abstract

A high energy double-pass master oscillator power-amplifier system has been developed, in which the oscillator is a passive Q-switch Nd^{3+}:YAG/Cr^{4+}:YAG microchip laser and the amplifier is a Nd^{3+}:YAG laser crystal longitudinally-pumped with a high-power diode. Laser pulses of ~1.5 *ns* duration in a TEM_{00} mode are generated from the microchip laser, while their energy is increased up to 20 *mJ* by the power-amplifier. Moreover, the laser can be operated in single or dual-pulse mode with an inter-pulse delay of ~ 50 ± 10 μs; and with a repetition rate from single shot up to 100 *Hz*. The developed laser device is aimed, but not limited, to selectively recover high value aluminium alloys from end-of-life vehicles waste, by means of a Laser Induced Breakdown Spectroscopy technique. The unique characteristics of the laser provide sufficient depth of field to accommodate scrap pieces of different heights (±2 *cm*), arriving at a velocity of 2 *m/s* and at different angles (± 12°).

Keywords: Micro Processing; System Technology; MOPA laser system; Recycling; LIBS

1. Introduction

Laser technology has been used in all kind of applications over the years, especially, in manufacturing or similar industries. Recently, one application in particular that draw our intention consists in a selective recovery of high value aluminium alloys (cast vs. wrought, or non-aluminium) from the so growing amount of waste generated by end of life vehicles (see for instance Margarido *et al.*, 2014). To address this issue, the approach we developed within the project ShredderSort (sported by the European Commission Grant Agreement Nr. 603676) is a novel sorting technology based on Laser Induced breakdown Spectroscopy

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(LIBS). This project addresses a major technological improvement that will increase the throughput to enable processing industrial waste volumes. This was achievable by combining six high performing passive Q-switch laser devices, together with a high throughput multichannel polychromator. In the following, we report on the developed laser devices.

2. From low to high energy passive Q-switched laser

The laser device is a master oscillator power amplifier (MOPA) in which the master oscillator is a passive Q-switch Nd^{3+}:YAG/Cr^{4+}:YAG microchip laser and the power or energy amplifier is a Nd^{3+}:YAG laser crystal longitudinally-pumped with a high-power laser diode. Such laser architecture was chosen in order to achieve high pulse energy values (Koechner, 2006). The microchip laser is formed by:

- a gain medium, which is a Nd^{3+}:YAG crystal that generates laser emission at 1064 *nm*,
- a saturable absorber material, which is a Cr^{4+}:YAG crystal, that allows under some conditions to generate Q-switch laser pulses.

Both crystals are bonded together to form a monolithic block of just 7 *mm* in length. The laser resonator is limited to the end faces of this block, with the laser high reflector mirror been deposited on the gain medium input face, while the output coupler been deposited directly on the saturable absorber crystal. Under the right configuration of the pumping power, the initial transmission of the Cr^{4+}:YAG crystal, and the total length of the microchip laser, it is possible to generate laser pulses of ~1.5 *ns* duration in a TEM_{00} mode (see for instance Tsunekane *et al.*, 2010; Kofler *et al.*; 2010, and the references within). However, when good laser beam quality and single mode operation are favored, pulse energy is limited.

In order to increase the energy of the Nd^{3+}:YAG/Cr^{4+}:YAG microchip laser pulses, we used it as the "seed" signal in a double-pass MOPA system, where the power amplifier is a longitudinally pumped Nd^{3+}:YAG crystal with a fiber coupled high power diode laser. Fig. 1 describes the developed double-pass MOPA device.

Fig. 1 (a) is a block diagram representing the different elements of the double-pass MOPA device, which will help us to explain how the double-pass amplification concept works:

- The "seed" signal is generated by the microchip laser;
- A half-wave plate ($\lambda/2$) is used to rotate and set the "seed" laser light to p-polarization;
- The polarizer beamsplitter will reflect s-polarized light at 45° angle, while it transmits p-polarized light;
- The p-polarized "seed" signal is thus transmitted and travels through the optical amplifier (first-pass);
- A quarter-wave plate ($\lambda/4$) is used to rotate the amplified laser beam by 45°;
- A mirror coated to provide high reflection at 1064 *nm* is used to totally reflect back the laser beam;
- The beam will pass again through the quarter-wave plate element, and its polarization is rotated an additional 45°, resulting in a total of 90° rotation, *i.e.*, the laser beam became s-polarized and travels in the opposite direction;
- It travels through the active media of the optical amplifier (second-pass) and is amplified a second time.
- When the double-pass amplified laser beam reaches the polarizer, it will be totally reflected at a 45° angle.

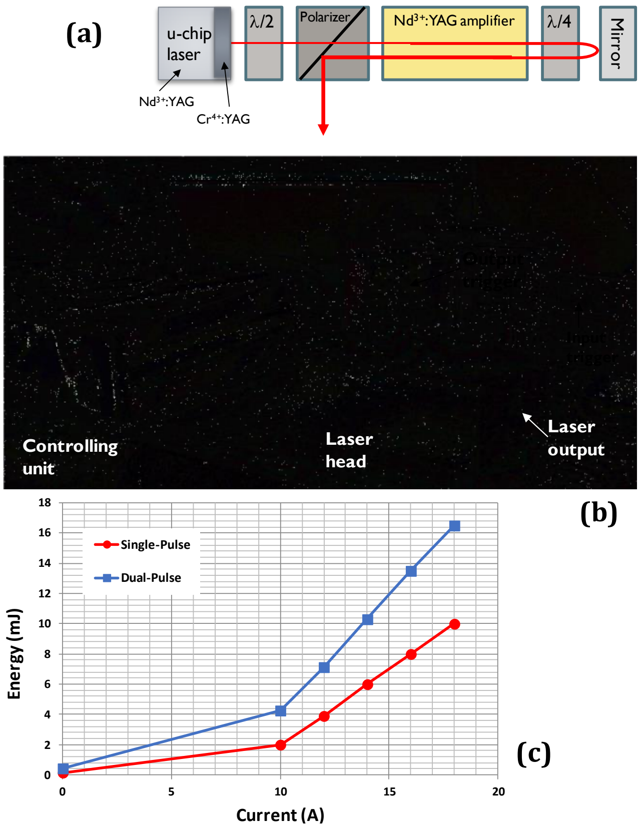

Fig. 1. (a) Block diagram of the double-pass amplification setup; (b) picture of the laser device, and (c) plot of the laser pulse energies vs. the current applied to the optical amplifier (the laser can be operated in single or dual-pulse modes).

Fig.1 (b) shows an image of the MOPA device, which is formed by a laser head and a controlling unit. The controlling unit allows to set the applied current of the optical amplifier (and thus the maximum energy of the laser pulses), the firing of the laser pulses (which can be trigger internally or external from single shot up to 100 *Hz* repetition rate), and generates after each laser firing an output transistor-transistor logic (TTL) signal that can be used to trigger for instance the LIBS signal analysis and integration. It is worth noting that both the laser head and the controlling unit are air cooled.

If the pumping fluence of the Nd^{3+}:YAG/Cr^{4+}:YAG microchip laser is increased multiple laser pulses can be generated (Tsunekane *et al.*, 2010). In our case, we set two values of the pumping power of the microchip laser that allows us to operate the "seed" signal in single pulse or dual-pulse mode with a time-gap of ~60 μs. Fig. 1 (c) represents a plot of the laser pulse energy as a function of the current applied to the optical amplifier in both single and dual-pulse operation modes. The generated "seed" pulse energy is 0.15 *mJ* in single-pulse mode and 0.43 *mJ* (0.21 + 0.21 *mJ*) in dual-pulse mode. At an applied current of 18 *A*, the amplified laser pulse energy was fond about 10 *mJ* in single-pulse mode, and a total of 16.5 *mJ* (8.25 + 8.25 *mJ*) is generated in dual-pulse mode.

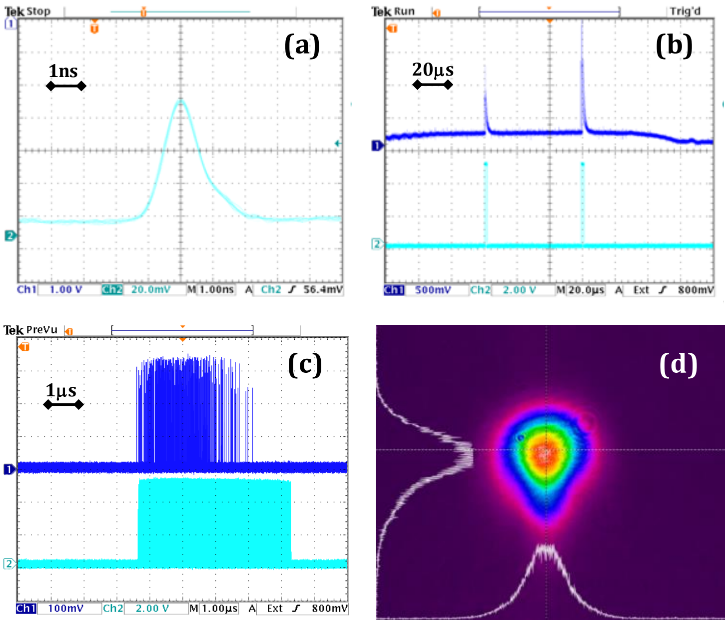

Fig. 2. Laser device characterization: (a) Laser pulse duration, (b) time gap between pulses in a dual-pulse mode, (c) laser pulse timing jitter and (d) amplified laser beam profile.

3. Laser device characterization

The laser pulse duration was measured by a 1 *GHz* low noise photoreceiver (New Focus Inc.) and displayed with a two-channel oscilloscope (Tektronix TDS3052B). Average pulse duration of ~1.5 *ns* was found as shown in Fig. 2 (a). Fig. 2 (b) and (c) represents the signals recorded by the photoreceiver and generated by the controlling unit after each laser firing, which are represented in Ch1 or Ch2, respectively. In Fig. 2 (b), two successive pulses when the laser is operated in dual-pulse mode are shown, and a time gap of ~60 μs has been found.

To determine the timing jitter of the laser pulses, we used the external trigger as the time reference and recorded over 500 laser shots using the photoreceiver. The 500 pulses are overlaid in Fig. 2 (c), where one can observe that the laser pulses are confined in a ~4 μs window, implying a timing jitter of ± 2 μs.

The laser beam profile at different positions in the propagation path has been analyzed by a laser beam imaging system (Ophir-Spiricon). Fig. 2 (d) represents the laser beam profile we measured at a distance of 450 *mm* from the laser output. The near-Gaussian shape confirms the TEM_{00} mode of the laser beam. The measured beam diameters (in *x* and *y* directions) at different positions of the propagation direction (*z*) are given in Table 1. A beam size of 0.8 x 1 *mm* at the laser output has been estimated, while the full angle divergence of the laser beam was found about ~3.6 *mrad*.

Table 1. Laser beam size measured at different positions along the propagation axis (*z*) and the resulting full angle divergence.

Direction	Beam diameter (*mm*) in the *z* direction		Full angle divergence (*mrad*)
	@ 100 *mm*	@ 450 *mm*	
x	0.95	2.2	3.57
y	1.1	2.45	3.85

4. Conclusion

We developed a double-pass master oscillator power amplifier laser system, in which the oscillator is a passive Q-switch Nd^{3+}:YAG/Cr^{4+}:YAG microchip laser and the amplifier is a Nd^{3+}:YAG laser crystal pumped with high-power fiber-coupled diode. The main characteristics of this device are:

- It can be operated in two operation modes (single or dual-pulse);
- Laser shot energy was found about 10 *mJ* in single pulse mode and > 16 *mJ* in dual-pulse mode. With a different configuration of the pumping of the microchip laser, pulse energy > 20 *mJ* can be achieved;
- Laser pulse duration is found ~ 1.5 *ns*;
- Laser beam analysis revealed good beam quality;
- The inter-pulse delay in dual-pulse operation mode can be set at ~ 50 ± 10 μs;
- The laser can be operated from single shot up to a repetition rate of 100 *Hz*;
- Laser pulse timing jitter was measured about ~2 μs.

The developed MOPA system is integrated in a high-throughput sorting line, which is used to selectively recover cast and wrought aluminium from end-of-life vehicles waste, by means of Laser Induced Breakdown Spectroscopy. The unique characteristics of the laser provide sufficient depth of field to accommodate scrap pieces of different heights (±2 *cm*), arriving at a velocity of 2 *m/s* and at different angles (± 12°).

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