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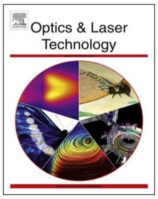

Full length article

Nanosecond double-pulse fiber laser with arbitrary sub-pulse combined based on a spectral beam combining system

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ABSTRACT

In order to improve the processing efficiency and quality of nanosecond pulse laser drilling, a new double-pulse technique is put forward. Two single pulse lasers with different pulse duration or different repetition rate are spectrally combined by a home-made polarization-independent multilayer dielectric reflective diffraction grating. The pulse energy of single lasers and the inter-pulse separation can both be set at one's option. Then, double-pulse lasers represent two closely conjoint pulses with tunable pulse duration and tunable repetition rate and tunable pulse energy and tunable inter-pulse separation are obtained.

1. Introduction

Due to the small heat-affected zone and independence of defects, short pulse lasers are widely used in material micro-fabrication processing, such as the manufacturing of oil gallery holes in engine blocks and the milling of explosives by femtosecond laser systems [1]. During the last decades, researches focused on laser processing are mainly concentrated in two aspects: 1) the damage mechanisms and characteristics of laser interacting with materials (metals, glasses, films and so on) [2–6]; 2) the improvement of laser processing efficiency and quality by means of changing laser parameters, environmental conditions, etc [7–13].

It has been found that the two main mechanisms responsible for material removal in pulse laser drilling are melt ejection and material vaporization. And the amount of material ejected in the liquid state has a direct effect on the laser drilling efficiency due to the fact that the material is removed without the loss of additional energy required for vaporization. However, the efficiency is usually rather low when the drilling is realized by a single pulse laser without gas-assist. And increasing the laser power does not work well because the resolidification of the molten pool. In order to improve the processing efficiency and quality of laser drilling, double-pulse techniques were proposed and attracted great interest. In 1975, Fox [14] firstly proposed combining a second sub-pulse to penetrate metal targets more efficient. They combined a CW CO_2 laser with a Q-switched Nd: glass laser to achieve a factor of 2 increase in the drilling efficiency of carbon steel and the hole of resolidified materials was much clearer. However, the drawback of this method is the presence of strong plasma screening. Because the pulse energy of the Q-switched laser is high enough to initiate a laser-supported detonation (LSD) wave effect. This wave absorbs the incoming radiation and shields the target. To overcome this problem, a combination of a high-energy laser pulse for melting with a properly tailored high-intensity laser pulse for liquid expulsion was demonstrated by Lehane and Kwok [15] in 2001. The pulse duration of the two sub-pulses was 3.5 ms and 0.15 ms, respectively. And the intensity of the short free-running laser pulse was seven times smaller than the LSD threshold. The influence of the interval time between the two pulses to the drilling efficiency was studied and an optimal delay time was found. However, the shortest free-running laser pulse they can achieve is 0.15 ms, which is not suitable for precision machining. In 2005, Forsman et al. [16] reported a nanosecond double-pulse laser with 3 ns pulse duration and several tens of nanoseconds inter-pulse separation to increase the rate and quality of large-aspect ratio (> 10:1) holes fabrication. The results had shown a significantly enhance (3–10 times) material removal rates while minimizing redeposition and heat-affected zones. But the producing process of the nanosecond double-pulse laser was not mentioned. After that, Wang et al. [17] reported a nanosecond double-pulse with 21 ns pulse duration and 52 ns inter-pulse separation for Laser drilling of stainless steel in 2009. The number of pulses for drilling through the

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samples and the average drilling rates were investigated with different laser fluences, sample's thickness, repetition rates and ambient gas pressures. The double-pulse laser was obtained from a single laser which was provided with a delayed divided pulse scheme. The time delay control between the two split parts was realized by some mirrors. The tuning accuracy of inter-pulse separation is difficult to control. Compared with two individual sub-pulse lasers, the laser parameters adjusting of single lasers is limited and inflexible, which means the pulse duration and the repetition rate are always remained to be the same. For applications which need a short and a long pulse combining, it is incapable. Last year, Pan et al. [18] proposed a new form of double pulse composed of a nanosecond laser and a millisecond laser for laser machining transparent materials. Different with the laser machining metals, laser processing transparent materials put forward a new requirement for the combined double-pulse shapes: defects to the irradiation area should be introduced before the following interaction process. So, the combined pulse laser with a short and a long pulse is more competent. The ns laser firstly irradiates the sample and causes modification at the surface, then the ms laser irradiates the same part after a certain time. The processing efficiency can be improved [19,20].

So, if one system can satisfy all the above requirements for the combination form of two sub-pulses, why not choose it?

In this paper, we proposed a new technique to produce the nanosecond double-pulse laser. A beam-combining element, refer to multilayer dielectric (MLD) reflective diffraction grating, is used to combine two single pulse lasers. The single laser emitters are modulated individually and the inter-pulse separation setting is realized by a commercial arbitrary waveform generator (AWG), which is also used for supplying a radio-frequency (RF) signal to modulate a CW laser into a pulse one. Three typical double-pulse shapes are presented below: 1) two closely conjoint pulses with same pulse duration and same repetition-rate but different pulse energy; 2) two closely conjoint pulses with same pulse duration but different repetition-rate and different pulse energy; 3) two conjoint pulses with different pulse duration and different pulse energy but same repetition-rate.

2. Experiment and discussion

The experimental setup consists of two identical fiber amplifiers and a MLD grating, which is shown in Fig. 1(a). The grating has a size of 50 mm×50 mm×2 mm and a period of 1040 nm (960 lines/mm line density). The measured diffraction efficiency versus incident beam wavelength from 1040 to 1090 nm is over 95% for both TE-polarization and TM-polarization. The central wavelength of the two single pulse lasers is 1064.4 nm and 1067.8 nm. The single pulse fiber amplifier system based on a master oscillator power amplifier (MOPA) structure is shown in Fig. 1(b). It includes an intensity-modulated pulse seed and a two-stage amplifier module. The pulse seed is obtained from a single-frequency CW laser, which is modulated by an electro-optic amplitude modulator (EOAM). The AWG outputs RF signal with tunable pulse durations and repetition rates is used to drive the fiber-based EOAM. To ensure the uniformity of trigger time for the RF signal, a common AWG is shared for the two seeds. When setting the RF signal generated by the AWG with 10 MHz repetition rate and 4 ns pulse width, the output optical pulses with 0.6 mW average power, 10 MHz repetition rate and ~5.6 ns pulse width are obtained. A pre-amplifier (Amp1) with 600 mW single-mode LD and 1 m Yb-doped single-cladding fiber (YSF) is used to amplify the seed average power from 0.6 to 200 mW. 20 W isolators (ISO) are inserted behind the seed and Amp1 to protect the optical components from damage of backward lights. The second stage amplifier (Amp 2) amplifies the average power to ~50 W directly. Amp 2 is clad pumped by three 27 W LDs via a (6+1)×1 combiner and the gain fiber is a 1.5 m 15/130 μm Yb-doped double-cladding fiber (YDF). The diameter of the laser beam output from the collimator is ~3 mm.

Since the grating is polarization-independent, no polarization control is needed for single pulse lasers. In order to make the two beamlets overlapped in both near and far field, a group of folding mirrors (HR 1050–1090 nm @45°) is used to adjust the wavelength dependent angle of incident. And the grating is aligned in first-order Littrow configuration at an angle of 30.58° (corresponding to a wavelength of 1060 nm) in the dispersive plane. The 3 nm spectral spacing between the two channels results in an angular dispersion that provide enough spatial separation at a distance of 4 m between the final folding mirrors and the dispersive element. The combined output beam is separated into two parts by a beam splitter which removes about 99.5% of the combined beam for power monitor and leaves the rest 0.05% for beam measurement.

When the average power of 1064 nm and 1067 nm is amplified to 54 W and 50 W respectively, the maximum combined output average power is 98 W and the diffraction efficiency is 94%. The near-field image of two single laser beams and the combined beam is shown in Fig. 2. The measured M^2 value of two single laser beams are both 1.5 (M^2_x=M^2_y=1.5), but the beam quality of the combined laser shows a ~0.3 drop in horizontal direction (M^2_y=1.5, M^2_x=1.8) at the full output average power. The degradation is influenced by spectral bandwidth (Δλ~60 pm), grating pitch (Λ=1042 nm), and beam waist (ω~3 mm). It can be calculated from $\Delta M^2_x = \omega\cdot\pi\cdot\Delta\lambda/(2\cdot\lambda\cdot\Lambda\cdot\cos\Theta_{\mathrm{Littrow}})$ [21] and the

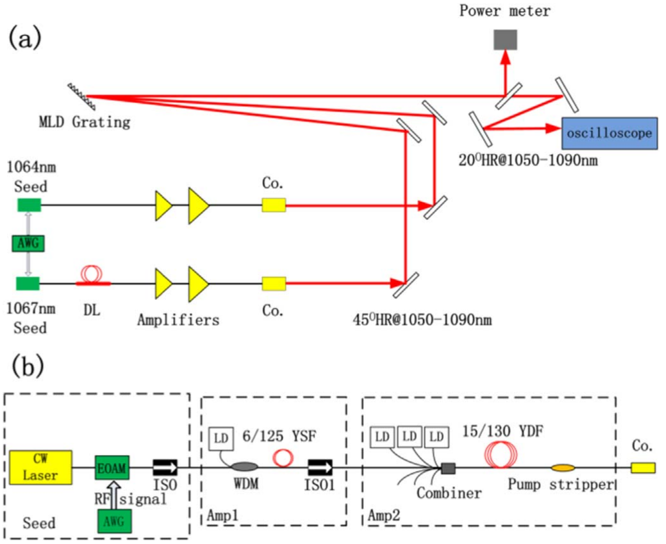

Fig. 1. Experimental arrangement of the double-pulse laser generation. (a)Beam combining of two single pulse laser emitters; (b) one of the two single pulse fiber amplifiers.

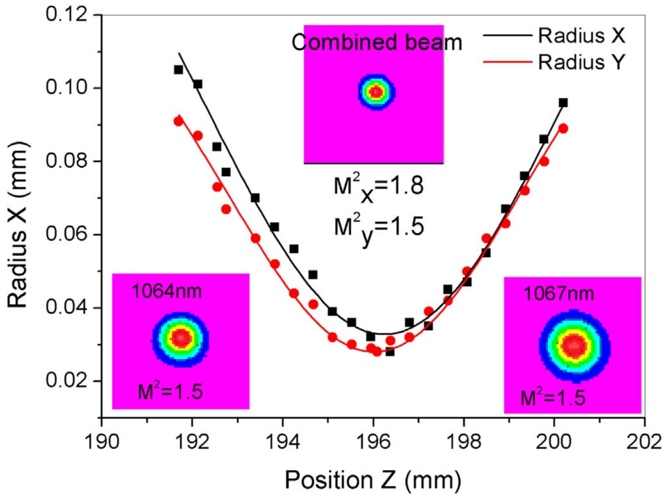

Fig. 2. The measured beam quality of two single laser beams and the combined laser beam.