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MOPA pulsed fiber laser for silicon scribing

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ABSTRACT

A 1064 nm master oscillator power amplifier (MOPA) pulsed fiber laser is developed with flexible control over the pulse width, repetition frequency and peak power, and it is used to investigate the dependence of mono-crystalline silicon scribe depth on the laser pulse width, scanning speed and repeat times. Experimental results indicate that long pulses with low peak powers lead to deep ablation depths. We also demonstrate that the ablation depth grows fast with the scanning repeat times at first and progressively tends to be saturated when the repeat times reach a certain level. A thermal model considering the laser pulse overlapping effect that predicts the silicon temperature variation and scribe depth is employed to verify the experimental conclusions with reasonably close agreement. These conclusions are of great benefits to the optimization of the laser material processing with high efficiency.

1. Introduction

Pulsed lasers find more and more micromachining applications ranging from ablation, cutting, drilling and marking. A wide array of publications have discussed the laser materials processing using a variety of lasers [1–3]. It is noted that the laser machining process is defined by the specific lasers used, and the optimization of a machining process involves the adjustment of multiple laser parameters, e.g., pulse width, average power, pulse energy and repetition frequency [4–6]. However, a variety of pulsed lasers in use, such as diode-pumped Q-switched lasers comprising an intra-cavity Q-switch element, adjusting one of the laser's parameters would invariably lead to changes in other parameters [7,8]. As a result, the improvement of the performance of laser micromachining is limited by the operation capability of these pulsed lasers.

High power pulsed fiber lasers offer a compact, electrically efficient and stable alternative to conventional bulky solid-state lasers, and they are being widely used in industrial manufacturing. Among various pulsed fiber laser solutions, the MOPA approach is a particularly attractive regime, and it offers unprecedented levels of performance and flexibility. That is, the laser pulse parameters can be adjusted independently, while maintaining a constant beam quality [9–11].

In this study, a MOPA fiber laser at the level of nanosecond is developed, and it is used to conduct experiments that evaluate the effects of pulse width and laser scanning parameters on the ablation process of mono-crystalline silicon, while maintaining a constant average power. A theoretical thermal model is utilized to analyze the scribe depths in terms of temperature variation of silicon material, and the theoretical predictions agree well with the experimental results. It indicates that laser pulse width and scanning parameters have great influences on the material removal rate and debris accumulation.

2. Laser configuration and marking system

The schematic of MOPA nanosecond fiber laser system is shown in Fig. 1. The system consists of two amplifying stages, e.g., preamplifier and power amplifier. The modulated seed source is a pulsed laser diode at 1064 nm, with power, pulse width and repetition frequency that are variable and independently controlled. Both stages are based on Yb-doped fiber amplifier (YDFA). The preamplifier stage is forward pumped by a 915 nm, 10 W laser diode coupled with Yb-doped double-clad fiber (YDDCF) using a combiner, and it provides an amplification of the seed laser with gain

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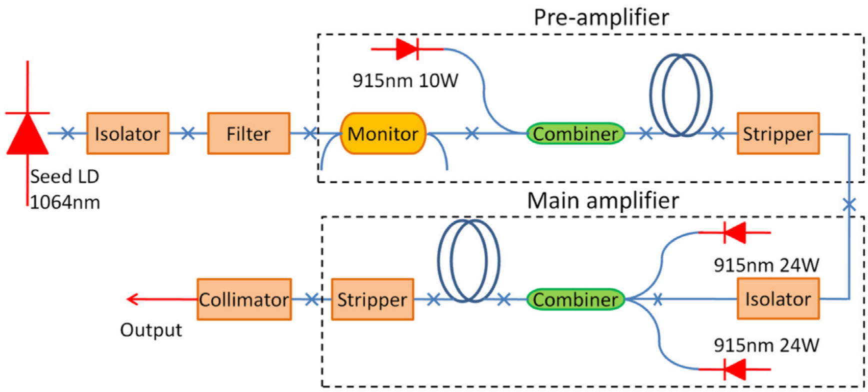

Fig. 1. Schematic of nano-second MOPA fiber laser system.

of 24 dB. A 2 × 2 fiber coupler, which is applied before the pre-amplifier stage, is for monitoring signal and back-reflection light without dismantling. The power-amplifier stage is cladding pumped by two 915 nm, 24 W laser diodes. Seed source and pre-amplifier stage, pre-amplifier stage and power-amplifier stage are separated with isolators which prevent the backward reflections and amplified spontaneous emission (ASE). The unabsorbed pump light from the two stages is rejected by self-made cladding-mode strippers. The system is terminated with an optically isolated fiber collimator, ensuring the reflections due to mismatch do not cause oscillations.

All the optical components are fixed on an aluminum plate for heat dissipation, and the whole system is enclosed in a box. As a result, a pulsed fiber laser is configured to emit pulses with an average power of 20 W, peak power up to 10 kW, pulse width ranging from 2 to 500 ns and repetition frequency of 20 to 500 kHz. The fiber laser is arranged in a marking station, consisting of a beam expander, scanner and projection f-theta lens, for delivery of laser beam on the target surface. The diameter of focused spot on the target surface is measured to be about 60 μm, which leads to peak irradiance level of about 0.35 GW/cm^2 and fluence level of about 7.1 J/cm^2 for pulse of 20 ns width and 100 kHz repetition frequency. It is worth noting that the MOPA pulsed fiber laser can be operated at a wide array of pulse configurations, and specific pulses with varying pulse widths are chosen in this work, while maintaining the same pulse energy (e.g., having the same average power 20 W and repetition frequency of 100 kHz). The scribing experiments are conducted on mono-crystalline silicon. The peak irradiance levels of pulses used in the experiment are well above the corresponding ablation threshold of silicon (the peak irradiance levels for pulse width of 20 ns, 40 ns, 100 ns, and 200 ns are 0.35 GW/cm^2, 0.18 GW/cm^2, 70 MW/cm^2, and 35 MW/cm^2, which are all above the corresponding ablation threshold of 27 MW/cm^2, 19.41 MW/cm^2, 10 MW/cm^2, and 8.68 MW/cm^2, respectively).

3. Theoretical model

A detailed modeling of the laser ablation process is quite complex as complicated mechanisms are involved in the ablation process. When processing with nanosecond pulse laser, the laser can be described as a heat source, and the heat equation can be applied to calculate the temperature evolution in the substrate. It is assumed that the laser radiation losses during scribing can be neglected, the heat conduction equation is approximately described by [12,13]

$$\rho C\frac{\partial T(r,z,t)}{\partial t} = K\cdot\nabla^2 T(r,z,t) + \alpha(T)(1-R)I_0(t)e^{-z\alpha(T)} \tag{1}$$

Where K is the thermal conductivity ($K=\kappa\rho C$), κ is the thermal diffusivity, ρ is the mass density, C is the thermal heat capacity, T is the temperature as a function of position (r, z) and time t, R is the Fresnel reflectivity of the surface, I_0 is the time-dependent incident laser intensity, and α is the absorption coefficient.

The general formulation for the temperature cannot be evaluated explicitly in Eq. (1). It is noted that the surface temperature would be well above the room temperature as the spatial overlap of the consecutive optical pulses being considered for the irradiated surface during the scanning process. Since the absorption coefficient of the silicon increases rapidly as the temperature rises [12], such that it is reasonable to assume that the absorption coefficient of the silicon is high enough to ensure most of the laser energy absorbed at the silicon surface. As a result, the temperature rise of the silicon due to absorption of an incoming Gaussian laser pulse, is given by [14]

$$\Delta T(r,z,t) = \frac{I_{max}\gamma w^2}{K}\left(\frac{\kappa}{\pi}\right)^{\frac{1}{2}}\int_0^{\tau}\frac{p(\tau-t)}{\sqrt{t}\left(4\kappa t+w^2\right)}e^{\left(-\frac{z^2}{4\kappa t}-\frac{r^2}{4\kappa t+w^2}\right)}dt \tag{2}$$

Where I_{max} is the peak power per unit area at the center of the beam spot, w is the beam radius, τ is the pulse width; γ being equal to $1-R$, is the fraction of the pulse energy that is absorbed by the material, and $p(t)$ is the laser pulse temporal profile.

Eq. (2) is used to predict the temperature distribution at the cross-section of the silicon as a function of depth z and radial distance r with respect to the center of the laser beam, considering that the radiation of a single pulse with a certain width is absorbed. During the simulation, $p(t)$ is assumed to be of a square shape for the MOPA fiber laser, which is quite reasonable especially for pulses with long widths. Other parameters used in the simulation are listed as follows, $w=30$ μm, $\kappa=0.907\times10^{-4}$ m^2/s, $K=145.3$ W/m K, $\gamma=0.69$, the boiling temperature $T_B=2628$ K [15]. Fig. 2(a)–(d) shows the calculated temperature distribution on the cross-section of silicon with pulses widths of 20 ns, 40 ns, 100 ns and 200 ns. The temperature contour follows the Gaussian distribution, and the temperature decreases as the depth and radial distance increases. The white line in Fig. 2 represents the boiling temperature of silicon at different pulse widths. Above the white line, the temperatures are high enough to sublimate of the material and well-defined ablation pits form. It also shows that a longer pulse with lower power can ablate a deeper pit than a shorter one with higher power, which is illustrated in Fig. 3.

It is quite straightforward to calculate the ablation depth $z(r)$ for a single pulse by setting the temperature rise ΔT being equal to the boiling temperature of the silicon minus the initial temperature in