Use of 1 ns-long pulses from an all-fiber-integrated laser-amplifier system in micromachining

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Abstract: We demonstrate micromachining with 1ns-long pulses from an all-fiber laser. Fiber lasers generating uncompressible long pulses have been ignored as undesired operational modes, however their robust, low-repetition-rate operation is well suited to micromachining.

OCIS codes: (140.4050) Mode-locked lasers;**(**140.3390) Laser materials processing; (060.2320) Fiber optics amplifiers and oscillators

Fiber lasers producing nanosecond, picosecond and femtosecond pulses are commonly used for various material processing applications, from precision micromachining to marking. The advantages (such as simplicity of the system, high material removal rate) and disadvantages (significant heat-affected zone, larger feature sizes) of nanosecond pulses over sub-picosecond pulses are well known. In the sub-picosecond regime, there is an ongoing debate as the relative advantages of picosecond and femtosecond pulses and it appears that there is no ideal pulse duration. It seems, rather, an optimization based on the specific application type and material in use is needed.

Here, we present micromachining results obtained with 1-ns-long pulses generated by a simple fiber laser, with a minimal heat affected zone (HAZ). Over the past decade, a variety of mode-locking regimes have been identified [1]. A commonly encountered, but usually ignored mode is when the laser produces stable, but long pulses, which cannot be compressed to the transform limit and referred to as noise-like operation [2] or square-pulse generation [3], which is obtained at net anomalous-dispersion and net normal-dispersion cavities, respectively. An interesting prospect is to amplify the square-shaped pulses for use in material processing: the oscillator operates at low repetition rates, eliminating the need for pulse picking and produces ~1 ns-long pulses. A pulse of duration of 1 ns is long enough that sustained plasma formation leads to more efficient ablation, but short enough to limit the HAZ. The pulse-to-pulse fluctuations of operation in this regime are characterized for the first time and found to be <1%.

An all-fiber-integrated oscillator utilizing a nonlinear optical loop mirror (NOLM) [4] generates 1 ns-long pulses. Fig. 1 shows the schematic of the setup. Oscillator operates at a state in which the pulses accumulate a relative phase shift of ~ π in the Sagnac loop, which maximizes its transmittance. Fig. 2(a) shows the optical spectrum recorded from the 10% tap port of the isolator. Fig. 2(b) shows the temporal profile of the pulses as measured with a 50-GHz sampling oscilloscope and 12-GHz photodiode, with a combined rise time of ~30 ps. The pulse width is slightly less than 1 ns. The RF spectrum is clean of modulations down to -70 dBc (Fig. 2(c, d)). The short-term power stability of the pulse train is characterized by its relative intensity noise (RIN) obtained using the standard method [5]. The integrated noise over the range 3 Hz – 250 kHz corresponds to pulse-to-pulse fluctuations of 0.6%. The pulse train generated by the oscillator seeds the two-stage fiber amplifier, which is similar to the system described in [6]. The maximum output power is 16 W, corresponding to 5.14 μJ of pulse energy.

In order to test the utility of this system in microprocessing, we use a galvo scanner, followed by an f-theta objective, which focuses the beam to a spot size of 20 μm. As target, we use polished titanium surfaces. For this target approximately 2 W of average power is sufficient. For comparison, we use an industrial fiber laser producing 70 ns-long pulses and a home-built fiber chirped-pulse amplifier (CPA). The fiber CPA system is operated without the pulse compressor and delivers 20 ps-long pulses at [7]. Fig. 3 shows scanning electron microscope (SEM) images of processed Ti surface in comparison with the images for 20 ps and 70 ns pulses taken from [7]. The HAZ is clearly small compared to the nanosecond system, and essentially the same as that produced by the 20-ps system. Fig. 4 shows close-in images of the patterns created, where the holes have a diameter of ~35 μm. The deposits near the holes are predominantly TiO_2, as determined from EDX analysis and Raman spectroscopy. We also produced trenches on the titanium surface, scanning at a speed of 0.1 mm/s at 0.75 W of average power.

In conclusion, we have demonstrated, for the first time to our knowledge, the use of 1 ns-long, uncompressible pulses generated from an all-fiber-integrated Yb-fiber laser in precision micromachining. We compare the performance of the laser with an industrial nanosecond fiber laser and a home-built fiber amplifier system producing 20 ps-long pulses. The quality and repeatability of micromachining is similar to those obtained with picosecond pulses and better than with the nanosecond pulsed laser. To date, this mode of operation of fiber lasers has been largely ignored as an undesirable mode of operation. However, this regime occurs in a large portion of the phase space, exhibiting very high tolerance to environmental variations, rendering extremely robust operation.

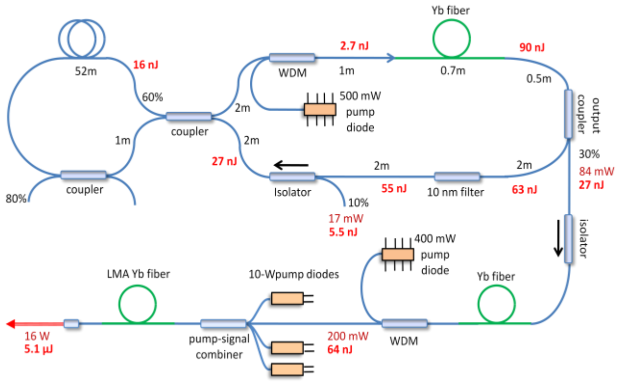

Fig. 1. Schematic diagram of the oscillator-amplifier setup. WDM: wavelength-division multiplexer; LMA: large mode area. The fiber lengths, powers and pulse energies are indicated.

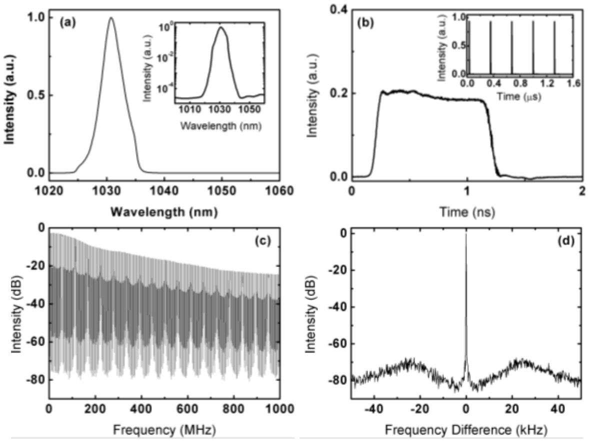

Fig. 2.(a) Optical spectrum of the pulse train measured at the 10% output port. (b) Pulse shape measured with a 30 ps-rise time sampling scope. Inset: Pulse train measured with a 1 GHz-bandwidth real-time oscilloscope.(c) RF spectrum of the pulse train. (d) RF spectrum of an individual comb line demonstrating low-noise operation.

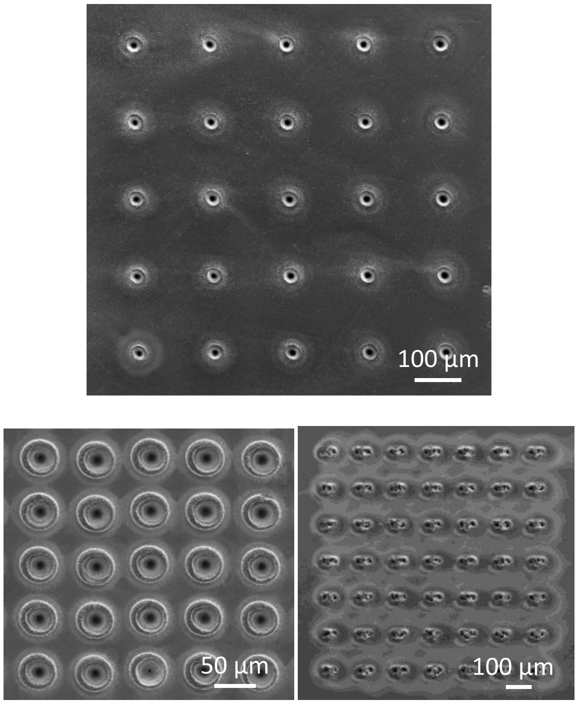

Fig. 3.Micromachined Ti surfaces using (a) 1 ns-long pulses in comparison with (b) 20 ps-long, and (c) 70 ns-long pulses.

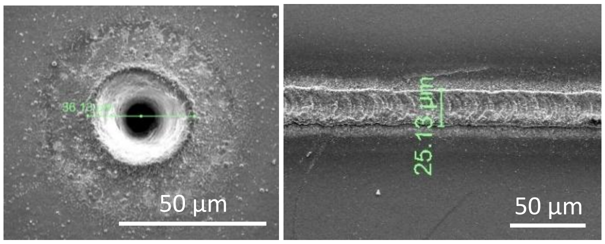

Fig. 4.(a) Close-up of a single hole with TiO_2 deposits nearby, and (b) a line pattern created by the 1 ns-long square pulses. No post processing or surface cleaning has been performed.

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