Femtosecond micromachining of high aspect ratio structures in fused silica using Bessel beams

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Femtosecond laser micromachining is a laser processing technology with proven potential for the fabrication of a wide range of photonic devices [1, 2]. In the context of developing integrated components for micro-fluidics, a key issue is the machining of high aspect ratio micro and nano-channels, and the use of diffraction-free Bessel beams for this purpose has attracted much attention [3, 4]. However, although Bessel beams possess several attractive characteristics for this purpose, we show here that their practical use for high aspect ratio micromachining requires a careful selection of focussing and pump laser parameters. We report results of a systematic study of Bessel beam micromachining of structures of diameter < 5µm in fused silica, and we describe conditions under which high quality and high aspect ratio structures can be reproducibly obtained.

Our experimental set up use a 100 fs, 800 nm amplified laser chain, with variable repetition rate selected using a pulse picker. Bessel beams were generated by applying a phasemask with rotational symmetry on a spatial light modulator. We produced a Bessel beam with a central lobe of diameter 1.5µm FWHM with 150µm longitudinal extent. The inset of Figure 1(a) shows the experimental image of the transverse beam profile. The first experiments compared results using frontside and backside machining geometry. With frontside machining, the redeposition of debris on the sample surface strongly lowers the ablation threshold leading to deleterious ablation by the side lobes of the Bessel beam. It is well known, however, that immersion drastically reduces this effect [5] and to allow for the evacuation of bubbles while maintaining a reasonable laser pulse repetition rate, we performed micromachining by focussing the Bessel beam on back side of fused silica samples. The roles of fluence, shot number and repetition rate were investigated.

With this setup, there are two major parameters that must be precisely controlled to yield high quality structures. Firstly, at any given repetition rate, a minimum pulse energy is required to surpass the machining threshold but on the other side, increasing the energy per pulse leads to degraded structures due to nonlinear propagation and beam collapse. The results in Figure 1(a) show that in a window of energy from 7 to 8.5µJ / pulse, microchannels of >40µm in length can be produced with high repeatability. The diameter of the channels only slightly increases from 2 to 3µm when the energy per pulse was varied between 7 and 11µJ. However, best results are obtained for a careful selection of repetition rate. Figure 1(b) shows the evolution of channel length with repetition rate. For a constant number of pulses, the channel length increases when the repetition rate is decreased since matter removal is more efficient at low repetition rates. Under low repetition rate and above threshold energy, high quality channels with low taper have been drilled such as shown in inset to Figure 1(b). Additional results have shown the machining of trenches in fused silica with near-parallel walls (<3° deviation from vertical), with potential applications to wafer dicing.

Within the parameter regimes identified here, Bessel beams present quantitative advantages when compared to diffractive Gaussian beams, especially for the drilling of channels of sub-10µm diameter. Outside this parameter regime, there is little benefit in the Bessel beam approach.

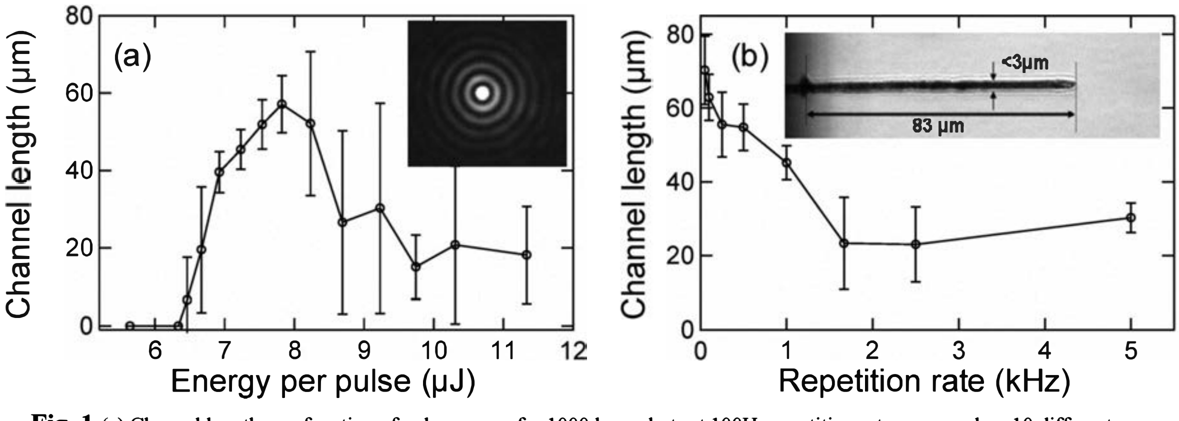

Fig. 1 (a) Channel length as a function of pulse energy for 1000 laser shots at 100Hz repetition rate, averaged on 10 different measurements. The inset shows the experimentally measured beam profile. (b) Channel length as a function of repetition rate for threshold energy and 1000 shots. The inset shows a typical machined structure at 50Hz repetition rate with 1000 laser shots.

References

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