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Micromachining of bulk transparent materials using nanojoule femtosecond laser pulses

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Abstract

Femtosecond lasers are very effective tools for three-dimensional micromachining of transparent materials. Nonlinear absorption of tightly focused femtosecond laser pulses allows energy to be deposited in a micrometer-sized volume in the bulk of the sample. If enough energy is deposited, localized changes in the material are produced (a change in refractive index, for example). These localized changes are the building blocks from which three-dimensional structures can be produced. With sufficiently tight focusing, the threshold for producing these changes can be achieved with pulse energies that are available directly from laser oscillators, offering greatly increased machining speeds and simpler, cheaper technology compared to using amplified lasers. In addition, the inter-pulse spacing from a laser oscillator is much shorter than the time required for energy deposited by one pulse to diffuse out of the focal volume. As a result, irradiation with multiple pulses on one spot in the sample leads to an accumulation of heat around the focal region. This localized heating provides another mechanism by which material properties can be altered. We demonstrate the three-dimensional fabrication of optical waveguides and microfluidic channels using pulse energies of only a few nanojoules to tens of nanojoules.

Keywords: femtosecond lasers, optical breakdown, micromachining, nonlinear absorption, waveguide, microfluidic

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With such a high numerical aperture as 1.4 how many times diffraction limited are you from your spot?

A: In all the experiments that I talked about today, we used focusing as high as 1.4 numerical aperature. We worked in cover slip glass, that's what Corning 0211 is, it's a cover slip. So a 1.4 N.A. objective is designed to focus at diffraction limit inside a cover slip. One problem with using these really high N.A. optics is that if we wanted to work in say, fused silica we have to design a new high numerical aperture optic; because the spherical aberration focusing into that would make the spot size many times diffraction limited. In these experiments we were diffraction limited but only because we worked in cover slip glass which the objective is designed to focus into.

Q - Sort of a related question, are you limited to the sample thickness then, that you can only focus in and you are sort of limited in sample thickness?

A: Correct. When you use high numerical aperture optics you are limited by the working distance of the optic. So for standard available microscope objectives, like from Zeiss, at 1.4 N.A., that working distance is a couple hundred microns. For the microfluidics we were using water immersion objectives; those are more closely matched to the refractive index of polydimethylsiloxane. In that case, water immersion objectives designed for in-vivo physiology experiments actually have a pretty good working distance. So they are with a numerical aperture of one; we had a working distance of two millimeters. All of these microscope objectives were really designed for observing biological specimens. If we went back and designed a lens for micromachining where we didn't need things like flat field and we didn't need lots of chromatic aberrations, then we could optimize for something like working distance and I don't think it would be a major obstacle to get working distances of several millimeters from these numerical apertures.

Q – These are fairly complicated optics with these high numerical apertures. Do you worry about pulse stretching by going through that much glass, is that a real problem?

A – Jeff Squire and Michael Mueller measured for this exact microscope objective that I used. They measured the dispersion of it. It's about 5,000 femtosecond squared. So for that, if you start with a 100 to 120 femtosecond pulse, you pretty much come out with a 105 to 125 femtosecond pulse, so it's really not a big deal. Now the waveguide experiments were actually done with a 20 femtosecond laser oscillator, so in that case we were very careful to compensate for the dispersion with a prism pair and measured the pulse duration at the microscope objective and we were able to recover the full transform limited pulse duration. Just for the simple prism pair.

Q – Just a comment, it's always an interesting thing, the first ever of three dimensional patterning using breakdown and transparent materials and so forth, there must be at least be a dozen companies that I am aware of that make their living by producing three dimensional objects using this phenomenon.

A – That's correct. Most of them use nanosecond laser pulses. But I've even seen in Monterey, there's this system that you sit down in front of multiple cameras that would take a photograph of your face, and then based on that, write a surface structure of you into a piece of glass using nanosecond laser induced breakdown. So it's not even that you have to have some kind of pre-conceived CAD file, it's gotten to the point where you can take a picture and then go write it into a piece of glass. The structure is there, it's pretty amazing looking.