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Simultaneous spatial frequency modulation imaging and micromachining with a femtosecond laser

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Abstract

A Ti:Al₂O₃ chirped-pulse amplification system is used to simultaneously image and machine. By combining simultaneous spatial and temporal focusing (SSTF) with spatial frequency modulation for imaging (SPIFI), we are able to decouple the imaging and cutting beams to attain a resolution and a field-of-view that is independent of the cutting beam, while maintaining single-element detection. This setup allows for real-time feedback with the potential for simultaneous nonlinear imaging and imaging through scattering media. The novel SSTF machining platform uses refractive optics that, in general, are prohibitive for energetic, amplified pulses that might otherwise compromise the integrity of the focus as a result of nonlinear effects.

The possibility to use a single setup for both machining and imaging is a feature of ultrashort pulse laser manufacturing that has been demonstrated multiple times in both linear and nonlinear modalities [1–5]. Live visualization of 3D morphological changes and damage thresholds has important implications for micromachining, allowing for real-time characterization and adjustment of cutting parameters. Currently, simultaneous write-characterization procedures with a single-laser system can be hindered by the inability to pass energetic (tens of micro-joules or higher) femtosecond pulses through the complex refractive optics demanded by a sophisticated optical delivery system. This is due to the introduction of an extended path length in glass which can result in significant accumulated nonlinear phase (B-integral) of the amplified beam. In addition, it is advantageous to be able to decouple the imaging and cutting beams to attain a resolution and a field-of-view that is independent of the machining beam.

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One of the key features of simultaneous spatial and temporal focusing (SSTF) [6,7] is that energetic femtosecond pulses can be passed through material without being inhibited by nonlinear effects [8], i.e., can be used to machine within the bulk of a substrate. SSTF most commonly uses a grating to spatially chirp the beam into a frequency-distributed array of beamlets [9]. A spatially chirped beam lowers the pulse intensity outside focus. A transform-limited, diffraction-limited, high-intensity pulse occurs only at the focal plane where all the frequency components cross. Notably, an appropriately designed SSTF optical delivery system can improve the axial intensity localization at focus while decreasing nonlinear effects outside focus [10–12]. The utility of SSTF beams has already been exploited in nonlinear microscopy to improve the frame rate and axial sectioning of wide-field two-photon excitation fluorescence (TPEF) microscopy [6,7,13] and to axially scan the focal plane by adjusting the group-velocity dispersion (GVD) of the excitation pulse [14]. However, machining with SSTF through refractive optics can be hindered by chromatic aberration, and the off-axis beamlets accumulate astigmatism and coma [15]. In previous efforts, it has been typical to use a reflective off-axis parabola to avoid these problems [8,10,16]. Additionally, early single-grating refractive SSTF arrangements [6,7] used for imaging, operated at high numerical aperture (1.4), large field-of-view (100 μm), and low pulse energies (nanojoules). SSTF for micromachining operates at different image conjugates, low numerical aperture (0.05), small field-of-view (10–30 μm), and high pulse energies (hundreds of microjoules). In this Letter, we demonstrate, through careful selection of available off-the-shelf optics, a low numerical aperture (NA) refractive optical delivery system that effectively combines imaging and SSTF micromachining. This type of delivery system is significant to enable industrial and clinical applications of SSTF femtosecond micromachining.

Important clinical applications include guided laser ablation within tissue. Such methods employ confocal detection due to the scattering nature of the target [17–22], and the necessity of visualizing layers above and/or below the target layer. In addition to concurrent imaging, real-time acquisition rates are desirable (25–30 Hz). Using a single-element detector mitigates the problem of scattering [23]. However, image acquisition rates with single-element detection can be further optimized by exploring scan geometries other than point scanning of a single focus [24–27]. Spatial frequency modulation for imaging (SPIFI) [28], as demonstrated here, appears well suited to this task, as it is able to acquire high-quality line images—with a single-element detector—concurrent with the generation of laser-machined features [29].

SPIFI uses a cylindrical lens to focus an imaging illumination beam to a line at the modulation disk. The modulation pattern,

$$m(R, \theta) = \frac{1}{2} + \frac{1}{2} \cos[(k_o + \Delta k R)\theta], \quad (1)$$

is an adaptation of the Lovell FM reticle [30,31] which imparts a carrier frequency as a function of radial (R) and angular (θ) position relative to the center of the disk. k_o is the spatial frequency offset of the disk in the radial direction. k is a measure of the maximum line density on the disk [28]. The carrier frequency encodes spatial information into

temporal frequencies which can be detected with a single-element detector such as a PMT or photodiode. The detected time-varying signal can then be Fourier transformed to retrieve a line image. Sanders *et al.*, to the best of our knowledge, were the first to form an image with frequency-modulated reticles [32]. More recently, Hoover *et al.* and Futia *et al.* showed that SPIFI is a viable option for both linear and nonlinear fluorescent imaging [23,28]. Howard *et al.* have used a similar technique for lifetime imaging [33].

In the simultaneous SSTF-machining SPIFI-imaging setup, a seed pulse originates from a 76 MHz repetition rate, Ti:Al₂O₃ oscillator operating at a measured central wavelength of 804 nm. The pulse width at focus, assuming a Gaussian pulse shape, was determined to be 85 fs full-width at half maximum (FWHM) using an interferometric second-order intensity autocorrelation [9]. The pulse train is sent through a pulse selector consisting of crossed calcite polarizers and a Pockels cell. The pulse selector sends a 1 kHz train to a standard chirped-pulse amplification (CPA) setup with an integrated single-grating SSTF compressor [9], while the rejected light is relayed to a SPIFI imaging setup [Fig. 1(a)]. The imaging setup consists of a 100 mm cylindrical lens that focuses the beam to an approximately 9 mm by 37 μm ($1/e^2$ diameter) line on a $k = 25$ lines/mm disk rotating at 25 Hz to frequency modulate the beam [Fig. 1(b)]. The frequency-encoded line focus is then image relayed to the sample plane using a pair of 1.6 $\times$ OCT scan lenses, each with a 109.9 mm effective focal length (Thorlabs LSM05-BB). Between the two scan lenses, a polarizing beam splitter (PBS) is used to introduce the cutting beam onto a collinear path with the imaging beam. After the sample, a second PBS is used to reject the high-intensity machining beam, while the imaging beam is transmitted and then collected onto a single-element detector (photodiode). Notably, any leakage light through the PBS from the machining beam does not interfere with the image, as it would in a traditional setup, since it is not within the image modulation band. The signal from the photodiode is collected using a data acquisition board (National Instruments USB-6341) and Fourier transformed to give spatial information along the line focus in real time. The data are processed into a 2D image by exporting and running an algorithm in a software package such as Matlab and Mathematica.

With our one-to-one image relay system, the lateral resolution along the extent of the line focus is defined as $\delta x = 1/k$. Therefore, the expected resolution with this setup is 40 μm [28]. This was validated independently by imaging a United States Air Force resolution test target (USAF1951) Group 3 Elements 2–6 (Fig. 2). The smallest line width we can resolve (Group 3, Element 6) is 35.08 μm which is in line with the estimated resolution of 40 μm based on the SPIFI mask line density. Since the NA of the OCT scan lenses is sufficient to capture the full diffraction of the modulation disk, the system's resolution is limited by the line pair density of the disk. Future work will extend the resolution to the limit of the NA of the optic.

For the machining beam, the performance of the LSM05-BB scan lens was analyzed using a CCD camera beam profiler (Thorlabs BC106N-VIS) to experimentally measure the focal spot of the SSTF beam and ensure an aberration-free focus (Fig. 3).

The SSTF machining beam was also analyzed through focus. For these measurements, the beam profiler was mounted on a manual translation stage and moved through focus in 5 mm

increments to ± 10 mm, where zero represents where the beam comes to a focus [Fig. 4(a)]. A through focus series was also modeled in ZEMAX, a computer-aided optical design and ray-tracing software, corroborating the experimental data [Fig. 4(b)].

To demonstrate the simultaneous machining/imaging capabilities of this system, a microscope slide (Premier 8201) was translated ± 0.5 mm in the y-direction using two-axis motorized Newport stages (LTA-HS/ESP301). The cut was made at 100 μJ per pulse and a speed of ~ 0.02 mm/s. The focal spot was ~ 94 μm measured as the $1/e^2$ diameter of the intensity. With this combination of focal spot, energy, and pulse duration, the laser affected zone extends significantly beyond the $1/e^2$ diameter as verified by the SPIFI images that follow. The resulting 2D SPIFI image is shown in Fig. 5(a). A line out of the channel is shown in Figs. 5(b) and 5(c). The transverse illumination beam profile is visible in the line out, and the machined surface features are visible as a decrease in line-out amplitude. We see that the SPIFI image clearly detects the channel being machined by the SSTF beam. Looking at a small section of the line out [Fig. 5(c)], we can determine the channel width is ~ 200 μm .

Figure 6 demonstrates the insensitivity of the SPIFI imaging technique to scattering. Even though the amplitude of the line out decreases with scattering, the machined channel maintains contrast. The performance of SPIFI in scattering media is described by Higley *et al.* [29], where they observed a 15% reduction in fringe, i.e., feature, visibility for ~ 97 scattering lengths in parafilm.

Combining SSTF and SPIFI, we have demonstrated the ability to simultaneously image and machine using single-element detection for the first time. No active gating of the SSTF machining beam was needed for imaging and, notably, this technique, unlike conventional 2D detection schemes, is robust to scattering ambiguity.

In summary, by employing SSTF with application to micro-machining, low numerical aperture beams can achieve axial confinement equivalent to their high numerical aperture counterparts. In addition, SSTF enables the use of refractive optics that facilitate optical delivery systems that can employ vital imaging diagnostics. In our case, we employ SPIFI for imaging, which has recently been shown to have the added benefit of super-resolved multimodal imaging [34].

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Fig. 1.

(a) Layout of the simultaneous machining and imaging setup. From the oscillator, a pulse selector comprised of two calcite polarizers (P1, P2) and a Pockels cell (P.C.) send an s-polarized, 1 kHz pulse train to the integrated S-STF/CPA system and a p-polarized, 76 MHz repetition rate pulse train to the SPIFI imaging setup. Each arm has a zero-order, half-wave waveplate (WP) to manipulate beam propagation through the two polarizing beam splitters (PBS). At the entrance of the SPIFI setup, two lenses ($L1 = 30$ mm and $L2 = 100$ mm) expand the beam by $\sim 3\times$ to fill the frequency-modulated reticle (mask) spinning at 25 Hz. A cylindrical lens (Cyl. L = 100 mm) creates a line focus on the mask. Scan lenses (SL1 and SL2), each with a specified effective focal length of 109.9 mm, relay the line focus image to the sample. The imaging beam is then collected on a photodiode. (b) Depiction of the frequency-modulation reticle.

Fig. 2. 1D SPIFI calibration line-out image of a United States Air Force resolution test target (USAF1951) Group 1, Element 1; and Group 3, Elements 2–6. The smallest line width we can resolve (Group 3, Element 6) is $35.08\ \mu\text{m}$ which is in line with the estimated resolution of $40\ \mu\text{m}$ based on the SPIFI mask line density.

Fig. 3. CCD camera beam profiler (Thorlabs BC106N-VIS) image of the SSTF beam at the focus of the LMS05-BB scan lens with the x and y cross sections overlaid.

Fig. 4.

(a) Through focus (± 10 mm) spot measurements from a CCD camera beam profiler of our SSTF beam with the LSM05-BB scan lens. (b) Simulated through-focus (± 10 mm) spot data of our SSTF beam with the LSM05-BB scan lens modeled in ZEMAX.

Fig. 5.

- (a) 2D simultaneous SPIFI image of a machined channel in glass. The horizontal blue line represents the region along which a spatial line out (b) of the machined channel was taken. (c) Enlarged view of the line out revealing a channel width of $\sim 200\ \mu\text{m}$.

Fig. 6. SPIFI line outs of the machined channel in glass. Line out “a” is the unobstructed image. Line out “b” is the image with frosted glass between the sample and detector. Line out “c” is the image with frosted glass before the sample. The small change in position (~ 0.5 mm) of the channel is due to spatial drift of the sample.