Spatial Frequency Modulated Imaging of Real-Time Laser-Matter Interaction

Confocal, Potentially Phase Sensitive Microscope with Reticle Modulation Mask

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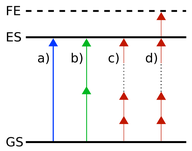
Abstract

Laser modification of materials or biological systems would benefit from imaging systems that are able to quantify the interaction in real-time. One of the important constraints for such an imaging system is that it must be robust against optical scattering, as interactions may take place deep within a scattering material.

Here, for the first time, we demonstrate confocal spatial frequency modulation imaging that can show real-time changes and make two and three dimensional images of the material. Single element detection is used to aid in mitigating scattering effects of the optical signal, and an 800nm excitation wavelength enables detection down to millimeter depths in glass and plastic scattering systems.

Multi-Photon and Infrared Microcopy



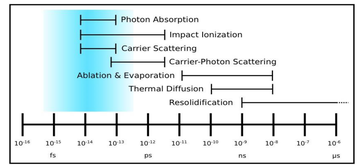
FE: Free Electron
ES: Excited State
GS: Ground State

Photon absorption:
a) single photon absorption, b) two photon absorption, c) multiphoton absorption, and d) multiphoton ionization[1]

Infrared microcopy is useful because it is less damaging to biological materials[3]. Shorter wavelengths, like UV, have enough energy to ionize the sample which leads to photobleaching, while longer wavelengths, like infrared, do not.

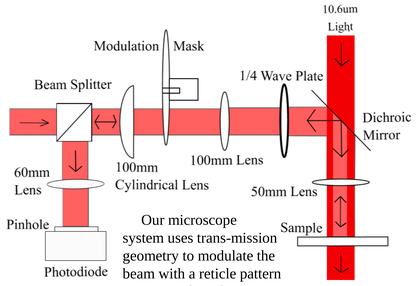
Femtosecond Pulsed Lasers

- Minimal heat deposited to material during removal
- Minimal interaction with material outside the focal volume
- Extremely high intensities (> 10^{12} W/cm^2) possible
- Sub-micron resolution over tens of cubic centimeters possible[1]



Timescales of Relevant Physical Phenomena[2]

SPatIal Frequency Modulated Imaging (SPIFI)

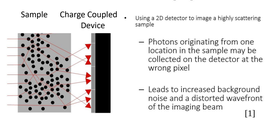


Our microscope system uses trans-mission geometry to modulate the beam with a reticle pattern on a rotated mask.

Background

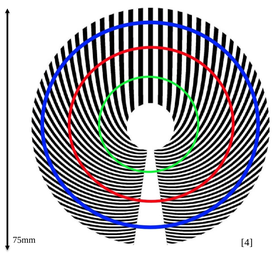
- In SPIFI the mask modulates the amplitude of the light at a specific frequency in the beam based on its location on the radius of the mask.
- Taking the Fourier Transform of the signal from the detector maps the signal back to the horizontal location on the mask and sample which eliminates scattering ambiguity.

Disadvantages of Non-Spatial Frequency Modulation for Imaging

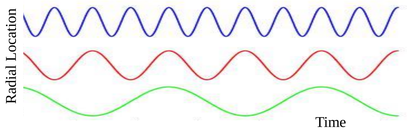


[1]

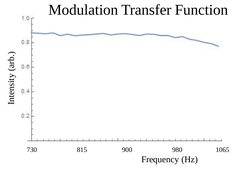
Modulation Mask



[4]



Modulation Transfer Function



- The modulation transfer function (MTF) shows from experimental data how much a particular mask will modulate the amplitude of the beam.
- The more uniform the illumination on the sample, the closer to an intensity of "1" and flatter the line is. This graph shows our mask has a very stable MTF.

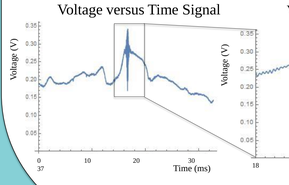
System Details

- 800nm Ti:Sapphire laser
- Average power of 78 mW
- Repetition rate of 76M Hz
- Pulse length of 80 fs
- Half-power spot diameter 13mm
- Mask rotates at 1600 rpm
- Dichroic mirror (transmits 10µm light, reflects 1µm)
- Dichroic used to integrate CO_2 laser
- Pinhole diameter of 600µm
- DET 100A Si Biased photodiode

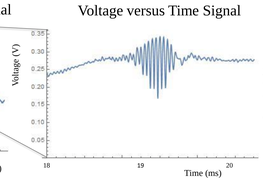
Data Collection

- Track the voltage vs. time signal from the photodiode.
- Take the fast Fourier transform to get the corresponding frequency of the modulated signal and its intensity at that frequency.
- The intensity vs. frequency graph shows a one dimensional image of the beam on the sample.
- By stepping the beam over the sample we create a two dimensional image of the sample's surface.

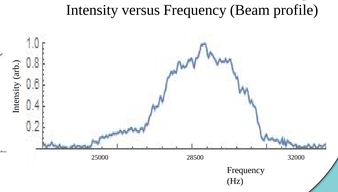
Time Domain
Voltage versus Time Signal



Voltage versus Time Signal

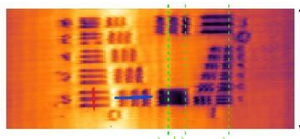


One Dimensional Fourier Domain Image
Intensity versus Frequency (Beam profile)

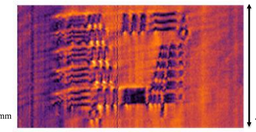


Resolution

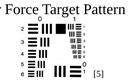
Fundamental Image



Second Order Image



Air Force Target Pattern

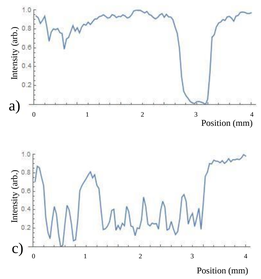


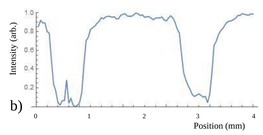
[5]

Actual size of Air Force Target Sample

3mm x 3mm

Intensity versus Position for Lateral Positions a, b, c





- A drop in intensity is where the sample scatters the light instead of reflecting it to be collected by the diode.

Theoretical Resolution

The smallest line pairs on the mask are 14µm, so this is theoretically our limiting factor for resolution. A 4f telescope focuses the beam to relay the mask to the sample with 0.5 magnification =>

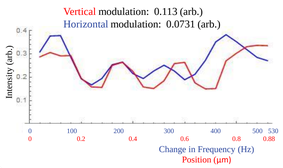
Theoretical Resolution = 7µm

Observed Resolved Features

On the Air Force Target the smallest features are visible in the image. These lines are 20µm apart, so we believe with improved alignment smaller features will be resolved.

Smallest resolved features = 20µm

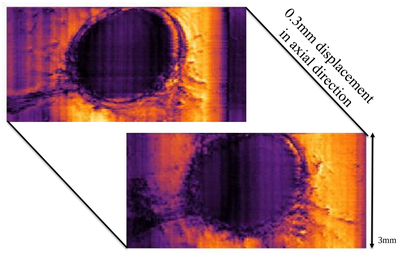
Vertical and Horizontal Modulation Depth



- There is a different horizontal and vertical modulation depth over lines with the same spacing inherently in the system design.
- The vertical resolution is determined by the step size taken between scans to create an image of a particular height with the desired number of steps. On this scan the step size was 0.25mm
- The horizontal resolution is determined by how fine the modulation of the mask is machined to be and by how accurately it modulates the beam. The smallest feature size machined on the our mask is 7µm.

Confocal System

CO_2 Laser Ablation on Copper Coated Slide



The features change as the specimen is scanned at different depths

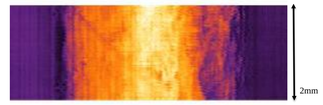
- In confocal microscopy illumination of the specimen is limited to a focused spot or line which is then scanned around the sample to get the full image.
- When this spot passes to the detector it is again limited by an exit pinhole to get rid of scattered light and signal not from the focus[3].

Properties of Confocal Microscopes

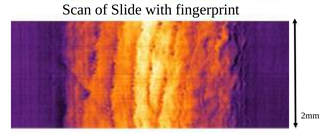
- Can be used in transmission or reflection geometries
- Detailed cross-sectional imaging is possible because signal from the sample not in the focus plane quickly drops off
- Improved signal to noise ratio
- Multiphoton absorption allows for the generation of images with different contrast mechanisms
- Creates much improved imaging of thick, light scattering materials[3]

Phase Imaging

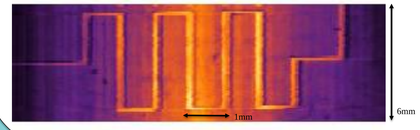
Scan of Clean Slide



Scan of Slide with fingerprint



Microfluidic Channels in Glass

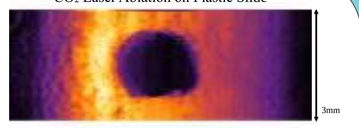


- The human eye is very sensitive to a certain range of colors, 400-700nm, but if an object is outside this range it is invisible to us.
- Phase objects are ones that are transparent but have features in them composed of different indices of refraction, like a clear sheet of plastic sitting on a clear piece of glass.
- The phase image of an object is created as the path length of light going through different features is changed.
- Fingerprints on glass are not visible to the human eye, but the lines of oil left by a finger have a different index of refraction than air and glass, so the finger print can be seen with phase-sensitive imaging.
- These microfluidic channels are almost invisible to the human eye, but can be clearly seen in phase.
- These images suggest that our system can see phase because the reconstructed images have greater contrast than can be seen by eye.
- Preliminary computational models suggest the system is sensitive to phase and analysis is on going.

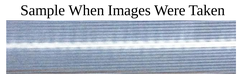
Conclusion

- We have demonstrated a novel new imaging modality that enables real-time characterization of laser ablation from a 10.6µm CO_2 laser. The resolution of the system was tested through imaging a series of line-pair targets fabricated in–house by our femtosecond laser micromachining system.
- Line-pairs down to 20µm were observed, which is greater than the calculated image resolution for the system. Improved alignment methods should enable diffraction-limited imaging.
- Finally, we imaged a fingerprint on acrylic and microfluidic channels in glass, which are both essentially phase targets. The image contrast obtained suggests that the system is capable of generating contrast based on phase differences in the target. We are working on new models of the microscope to help explain the apparent phase contrast.

CO_2 Laser Ablation on Plastic Slide



The Focus of the Modulated Beam at the Sample When Images Were Taken



The Improved Focus Possible with Realigning the Mask

References and Acknowledgements

References

[1] Worts, N.; Squier, J., *Advances in Ultrafast Laser Material Processing: Investigation of Novel Applications Involving Additive and Subtractive Manufacturing*, Colorado School of Mines Department of Physics Thesis Proposal Defense, **2017**.

[2] Worts, N., *Advances in 3D Ultrafast Laser Material Processing*, Colorado School of Mines Department of Physics Graduate Student Poster Session, **2016**.

[3] Pawley, J., Ed. *Handbook of Biological Confocal Microscopy*, Third Edition; Springer Science+Business Media, LLC: New York, **2006**.

[4] Futia, G.; Schlup, P.; Winters, D.; Bartels, R. Spatially-chirped modulation imaging of absorbtion and fluorescent objects on single-element optical detector. *Optics Express*. **2011**, Vol. 19, Issue 2, 1626-1640.

[5] Original USAF Resolution Charts, ProSciTech, https://proscitech.com/?navaction=show_page&chapter

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