Femtosecond Laser Practical Session

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1 Introduction

This report presents observations and results from the ultrafast laser practical session, focusing on its safety considerations, operational characteristics, and applications. The experiment aimed to explore the principles of ultrafast laser micro/nanostructuring and evaluate the outcomes of laser-material interactions under controlled conditions.

2 Safety Notions

The laser used in this practical session can be characterized as having a pulse duration in the femtosecond range (10^{-15} seconds) with the wavelength of the laser is in the infrared range (1030 nm) and the power of the laser is about 100 Watt/pulse . All of this to say the femtosecond laser emits a very large amount of energy during each pulse therefore large risks are associated with using such a laser.

When working in a laser laboratory, laser accidents can occur for many reasons. Some of risks associated with this specific laser are due to the infrared spectrum of the laser - the laser beam is impossible to see with the naked eye. Additionally, nonlinear interactions can cause unexpected reflections or scattering and polished or reflecting surfaces in the lab can allow a dangerous laser beam to be redirected into ones eye.

If one does not take special care to eliminate hazards in the laser laboratory, damage can occur to both the lab and the people within the lab. Eye injury resulting in partial or total loss of vision can be caused by direct exposure or scattered light. If a high powered laser beam enters the eye, the lens will focus the beam onto the retina. The retina contains a high concentration of specialized cells that alow us to see therefore a laser eliminating these cells will be detrimental to ones vision. Another type of injury that can occur to the eye happens when a laser beam comes in contact with the eye from the side rather than straight on. In this case, the laser will damage the cornea causing it to become misshapen and again damage ones vision. Additionally, skin burns can happen on exposure to high intensity beams. Finally, high-energy pulses can ignite flammable materials probing themselves as a fire hazard.

In order to reduce the risks of these types of accidents, it is important that all persons working in a laser laboratory are well aware of the safety precautious that are necessary. These precautions include always using proper laser goggles rated for the laser's wavelength, installing beam enclosures or barriers to prevent unintended exposure, posting warning signs near active laser setups, training personnel on safe laser operation practices, and avoid the using polished or reflective surface (including jewelry) while in the laser room.

3 Classical Gauss Configuration

The experimental set up is shown in figure 1. Not pictured is the scanner that allows the laser to move back and forth and create different patters on the engraving surface. The black optical box was introduced into the experimental set up as a safety precaution to limit the length of the lasers path that a person could be exposed to therefore decreasing the risk of injury.

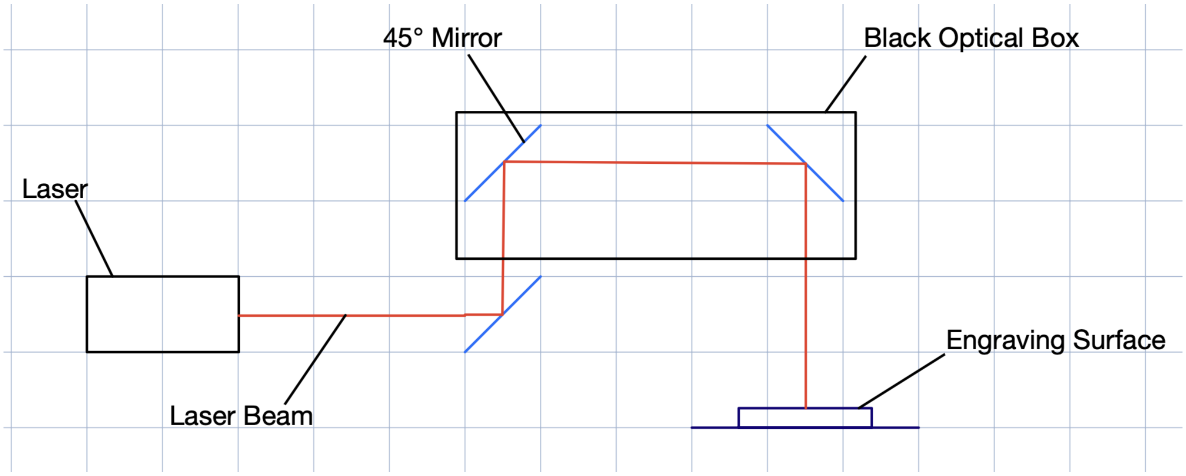

Figure 1: Experimental Setup Schematic (not to scale)

It was observed from the software screen that the laser beam arrived the surface in the Gaussian intensity profile similar to the one given in figure 2 below. The peak at the center represents the highest intensity, and it gradually decreases toward the edges, following the Gaussian distribution. This profile corresponds to a cross-section of the beam, showing how intensity varies with distance from the center. The width of the pulse is calculate at the half-peak.

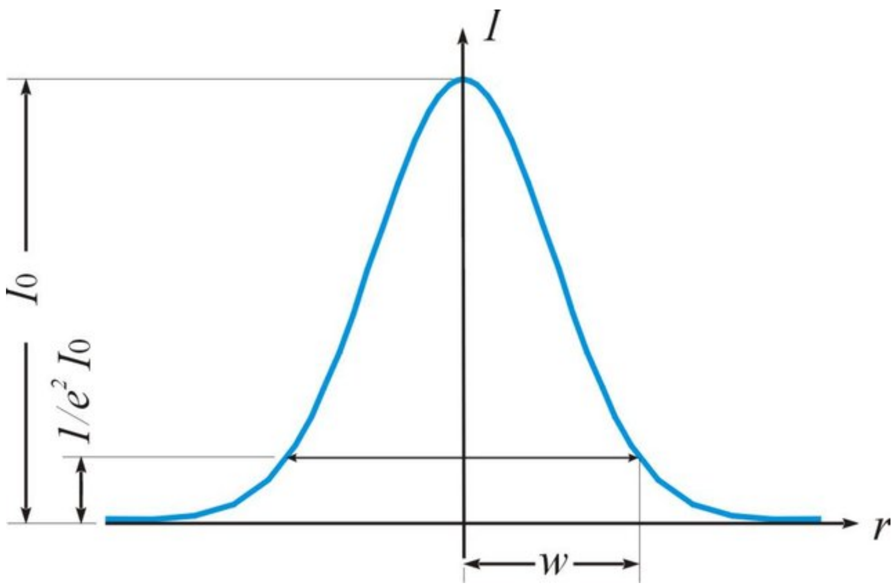

Figure 2: Laser Beam Intensity Profile

Figure 3 shows the power of the laser pulse verses the percent transmission as recorded by the sensor in the experiment. As the transmission percentage increases, the power output of the laser increases. Interestingly, the relationship is not linear but, better represented by a polynomial of the fourth degree.

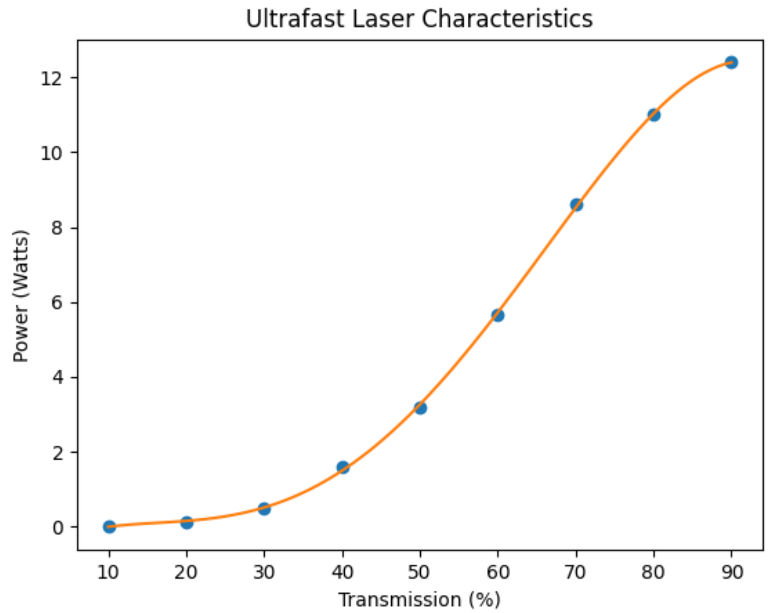

Figure 3: Ultrafast Laser Characteristics

The typical pulse repetition rate (PRR) for femtosecond laser is tuneable from 1Hz to 1MHz The laser used in this practical session had a pulse repetition rate of about 100 kHz or 100,000 pulses/second. Considering the laser at 30 % transmission resulting in the power of 0.5 Watts, operating in 1 second, the laser energy calculations are as follows:

$$Energy = power \cdot time$$

$$E = 0.5W \cdot 1s = 0.5J$$

$$E_{pulse} = \frac{Energy}{PRR}$$

$$E_{pulse} = \frac{0.5J}{100,000pulse} = 5 \cdot 10^{-6} J/pulse$$

Next, the fluence (energy density) was calculated. This value is important because it must reach a certain threshold - specific to the material it is acting on - in order for abbelation to take place. The laser spot diameter is calculated based on measurements taken prior to the session. The laser spot can be seen in figure 4. It is not a perfect circle therefore the average of the x and y diameters were taken to make the calculations. It is interesting to note that the Gaussian laser spot intensity can also be seen in this image.

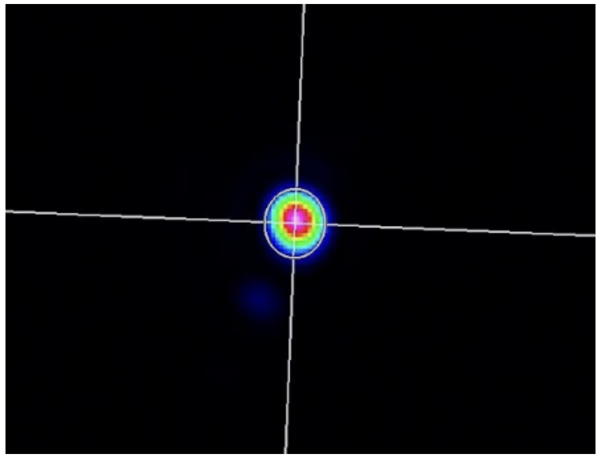

Figure 4: Laser Spot

Laser Spot Radius:

$$d\sigma_x = 33.03\mu m$$

$$d\sigma_y = 37.43\mu m$$

$$d\sigma = \frac{33.03\mu m + 37.43\mu m}{2} = 35.23\mu m$$

$$w_0 = \frac{d\sigma}{2} = 17.62\mu m$$

Laser Spot Area:

$$SurfaceArea = \pi\omega_o^2$$

Energy Density Formula:

$$Fluence = \frac{E_{Pulse}}{SurfaceArea} = \frac{5 \cdot 10^{-6} J/pulse}{\pi \ \cdot (1.762 \cdot 10^{-3} cm)^2} = 0.51 J/cm^2$$

4 Ultrafast Laser Micro/Nanostructuring

The process of creating a 2D pattern using ultrafast lasers for micro- and nanostructuring involves involves very precise techniques and an intersection of optical elements, mechanical components and computer aided pattern design. Primarily, high-intensity femtosecond or picosecond laser pulses which focus energy precisely onto a material are required to create abbelation. This enables nonlinear absorption and minimal heat diffusion within the lattice of the material. Nonlinear processes like multi-photon absorption achieve sub-wavelength precision. The material undergoes ablation, refractive index modification, or phase changes, forming micro/nanostructures. Next, galvanometer mirrors or translation stages are used to direct the laser beam across the surface in two dimensions to trace the desired pattern. The pattern is generated by a CAD software which also defines optimized laser parameters (pulse energy, overlap, focus) for feature size and resolution. High-NA lenses focus the beam to sub-micron spots, with spatial light modulators enabling complex beam shaping. Finally, real-time monitoring ensures precise structuring and compensates for deviations. This method produces intricate, highly accurate patterns for applications in a variety of fields requiring high prescision on a very small scale.

Evaluating the laser processing results can be done in multiple ways depending on the desired attributes of the specimen. Microscopic Analysis using SEM, optical, or confocal microscopy for surface inspection and feature resolution is a common way to asses the quality of a femtosecond laser nanostructuring. Additionally, surface profiling can be used to measure roughness, depth, and 3D structures with tools like AFM and profilometers if surface finish is an important outcome for the application. In order to test dimensional accuracy, feature sizes and tolerances can be verified against design specifications as can be done for any manufactured part. Phase changes or chemical modifications can be analyzed via Raman spectroscopy or diffraction. Optical, hydrophobic, or mechanical properties relevant to the application should also be assessed to guarantee functionality of the part. Lastly, statistical and comparative analysis may be used to ensure uniformity, repeatability, and alignment with the design or benchmarks. All of these processes ensures the features meet precision and quality standards that are clearly important for such precise applications.

Femtosecond laser micro/nano-processing has applications across many industries and fields. Some of these applications are in the field of optics and photonics where femtosecond lasers are used to fabricate wavehuides, grating, and anti-reflective surfaces. In electronics, this technology is used to structure semiconductors, make flexible electronics, and PCBs. The field of biomedicine may use femotosecond lasers to create microfluidic devices, biocompatible implants, and perform precises laser surgeries. The femtosecond laser technology has additional applications in a spectrum of other fields such as patterning solar sells, reducing friction on surfaces, producing thin films, creating anti-counterfeiting measures, and enhancing surfaces for better aerodynamics. Its precision and versatility drive advancements in diverse industries.