A low-cost setup for microstructuring experiments using a homemade UV laser

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We present a simple high school and university undergraduate laboratory setup, with which we are able to texture microscopic structures into polymer and dye films using a homemade UV nitrogen laser. We describe both the laser and the microstructuring setup and provide detailed information on the laser and its beam characteristics. Although this is a low-cost setup, we are able to directly write or texture high-quality patterns into thin films, either by manually controlling a positioning stage or by programming a desired sequence for an automated structuring process. We introduce several hands-on experiments for high school and university undergraduate students and present our first results.

I. INTRODUCTION

Superradiant nitrogen lasers with an emission spectrum centered at 337.1 nm, can easily be set up, as suggested in 1972 by Small and Ashari\(^1\) and Basting et al.\(^2\) This remarkable fact has been presented to a broader audience through the Amateur Scientist column in Scientific American.\(^3\) Subsequently, several follow-up papers have focused on circuit design\(^4,5\) and the underlying theory.\(^6,7\) Hilborn\(^8\) has presented a simple nitrogen laser pumped dye laser design for several demonstration experiments.

There are numerous other laser applications, such as material processing and laser cutting, which have direct technological relevance, either directly for industry or as enabling technology in other areas of science and technology. For instance, laser microbeams can be used for fine microdissection of chromosomes\(^9\) and direct laser writing is used for the fabrication of three-dimensional microdevices\(^10\) and three-dimensional nano-photonic materials.\(^11\) Since these fascinating research topics are worth teaching at an early stage, we have developed a simple microstructuring experiment for our high school and undergraduate university student laboratory. To do so, we have combined a homemade nitrogen laser with a simple setup that focuses the beam onto the sample which is to be structured. A micropositioning system allows the user to control the processing—either manually or by programming a pre-defined sequence via an easy-to-use graphical user interface. In addition, we have identified suitable sample materials for which different aspects of the use of UV-laser light in materials processing can be illustrated in a straightforward manner. This includes laser ablation of polyimide films as well as the ablation of thin dye films created using permanent markers.

II. HOMEMADE NITROGEN LASER

A. Laser setup

The laser operation is based on transverse excitation via plasma discharge (TE laser). The nitrogen is pumped by direct electron impact (Franck-Condon principle\(^12,13\)) on the nitrogen molecules. Our nitrogen laser, shown in Fig. 1, works with a standard Blumlein circuit design.\(^14\) The capacitors are made from aluminum foil with 60 μm thick Mylar\(^6\) films used as dielectric spacers. The laser chamber is made from acrylic
The Blumlein circuit works as follows. The capacitors are charged by applying a potential difference across the plates. The top plates of C1 and C2 are connected via a 4.7 kΩ resistor and are charged to the same potential. When the voltage gets high enough to induce a breakdown of the spark gap (SG), laser action is initiated: capacitor C2 is discharged and a steep potential difference is created between the electrodes in the laser chamber. The resulting discharge between the electrodes leads to a population inversion in the nitrogen molecules, and laser action is achieved via superradiant emission. This cycle repeats itself when the charging process is repeated.

The cost of the materials used for the laser setup is low. All you need are some aluminum sheets for the capacitor plates, two aluminum rods or rails for the electrodes, plastic or glass for the box, rubber seals for the laser chamber, and two screws for the spark gap. All these components can be purchased in a hardware store for less than 50 $. The resistor and the leads can be obtained in an electronics store for a few dollars. The vacuum pump and the power supply is standard equipment in most laboratories. Pure nitrogen is not necessarily required since the laser can operate with the nitrogen in ambient air, albeit at reduced power. Our nitrogen laser can thus easily be set up at high schools. In our school lab, the students usually assemble the nitrogen laser on their own; they are just given the components and the circuit diagram. We have found that building their own laser, seeing it work, and characterizing its properties is a motivating experience for our students.

B. Laser characteristics

The capacitor dimensions used in our laser are approximately 0.21 m × 0.3 m and the dielectric constant of the 60 μm Mylar® film between the plates is about 3.2. We estimate that the capacitance of the Blumlein circuit capacitors is about 30 nF. This value can be adjusted by changing the dimensions of the capacitor plates. The repetition rate depends on how fast C1 and C2 can be charged and when the breakdown in the spark gap occurs; this rate can be tuned by adjusting the width of the spark gap. An early breakdown prevents the capacitors from being fully charged and will reduce the output energy of the laser. We have found that a repetition rate of about 2 Hz is optimal. At this rate, the capacitors can be fully charged and the process is slow enough so that the structuring procedure can be easily observed and controlled by the students.

We have performed pulse energy measurements using a Coherent FieldMaxII–TOP energy meter with a pyroelectric J-25MB-LE sensor. The pulse width has been determined with a Thorlabs DET10A/M PIN photodiode detector and a storage oscilloscope. Figure 2(a) shows the pulse energy as a function of the chamber pressure for an input voltage of 12 kV, which delivers sufficient fluence for the structuring process. Higher voltages can be applied, but they increase the rate at which the dielectric and the aluminum sheets deteriorate. We observe a maximum laser energy of (60 ± 8) μJ per pulse at a nitrogen pressure of 120 mbar. In these measurements, the laser runs less stable at lower pulse energies which results in larger error bars. At higher pressures, more frequent molecular collisions lead to an increase in the deexcitation rate of the upper laser level. At lower pressures there are simply too few nitrogen molecules in the chamber to generate lasing action. Consequently, a chamber pressure of 120 mbar is most suitable for our microstructuring experiments and we have carried out all measurements described in the paper at this pressure.

Figure 2(b) shows the shape of a representative pulse, obtained using the Thorlabs photodiode. The pulse width is determined by fitting a Gaussian function to the measured pulse profile to obtain its full width at half maximum (FWHM). The average pulse width is (4.4 ± 0.3) ns. Based on these measurements, we conclude that the output power of the laser is about (14 ± 3) kW. This output energy and power
can be tuned in a number of ways. For instance, we have explored different capacitor sizes, operating voltages, and chamber pressures. We have found that the parameters discussed above are the most favorable for our microstructuring experiments. The spatial shape of the laser beam is largely determined by the shape of the laser electrodes and their separation. In our setup, we used pointed band electrodes with an electrode spacing of about 10 mm and the beam profile is elliptical. Additional lenses in the beam path can be used for beam shaping, but these increase the cost and reduce the fluence due to absorption. Figure 3 shows a microscope image of the beam spot, focused by our microscope objective, on a polymer film sample. From this image we can make a fairly good estimate of the shape of our structuring spot on the sample. The size of the spot’s image on the sample is about 80 \( \mu \text{m} \times 28 \mu \text{m} \) and the profile is highly asymmetric. In order to achieve a well-focussed spot for microstructuring applications, we have to fill the aperture of the focusing objective as much as possible. Since the beam profile of the output of the laser is very asymmetric and shows no well-defined shape due to the simple setup and electrode shape, one needs to find the optimal adjustment by trial and error. Based on the best resulting images we obtained, such as the one shown in Fig. 3, we have determined which circular region of the beam’s cross-section exhibits the highest intensity and have utilized this region to achieve the optimum illumination of the focusing objective. This procedure has proven to be adequate for our application.

III. SIMPLE MICROSTRUCTURING EXPERIMENTS

A. Laboratory setup

In order to perform microstructuring experiments, it is necessary to tightly focus the UV-laser spot onto the sample. Although this experiment is intended to be a low-cost setup, we must use fused silica optics to focus our laser beam. Standard BK7 optics are hardly transparent for ultraviolet light and are quickly damaged due to absorption of the intense UV-laser pulses of our setup.

Figure 4 shows the setup of our experiment. The beam focusing setup uses fused silica lenses and a Zeiss Ultrafluor objective (10 \( \times \) magnification, 0.2 NA). All optical components are mounted on a simple right-angle aluminum board which is installed in a homemade UV-protective housing. The laser pulse enters the setup on the lower left-hand side in Fig. 4. The first broadband mirror (mirror 1) directs the beam into an inverse telescope in order to reduce the beam...
spot size. The beam cross section at the exit of the laser is about 0.3 mm × 0.8 mm. The two lenses used have focal lengths of 100 and 50 mm and reduce this beam spot size by a factor of 2. By adjusting the separation between the lenses, they can also compensate for the divergence of the beam. Mirror 2 deflects the beam toward a beamsplitter or a cold mirror. The scattered beam is directed onto the objective of the microscope and focused onto the sample. A USB-microscope camera allows the user to observe the microstructuring process on a computer monitor.

Since it is much easier to move the sample than to steer the laser beam, the sample is placed on an x-y-z micropositioning stage (Thorlabs PT series). A pattern can be structured into the sample by moving the stage within the xy-plane with two independent stepper actuators, barely visible in the lower right corner of Fig. 4. This setup allows us to displace the sample by up to 12 mm in both directions. The actuators are driven by two controller cubes that can be operated either by software or manually. The software allows the students to program the entire motion sequence. Examples of images that have been microstructured into samples are shown in Fig. 5. The stepper motors can be moved continuously during the structuring process. Due to the good resolution of the motors (0.4 μm) compared to the size of the microstructures (a few hundred microns), vibrations are of little significance. The sample is moved along the z-axis to focus the beam.

The cost of the microstructuring setup described here is about $3,500; $2,600 is the cost of the motorized stage alone. Since the optical components must be suitable for UV light, they are more expensive than standard optics components and account for $700 of the total.

B. Materials and experiments

Before selecting materials suitable for microstructuring, we need to determine the fluence F of the laser pulses. The fluence can be calculated from the effective energy per pulse and its surface area. It will be affected by power losses due to absorption and reflection from the optical components in our system. Based on the measured laser power at the exit of the optical system and using the manufacturer’s specifications of the transmittance through the objective, we estimate that about 28% of the total laser output power is available for microstructuring. The major power-loss sources are the beamsplitter (40% loss) and the objective (27% loss). In addition, the asymmetric beam profile of the laser does not allow us to fill the entire aperture of the objective without cutting away part of the beam cross section. As a result, our setup reduces the maximum pulse energy from 60 μJ down to (17 ± 2) μJ. The beam cross section for microstructuring can be approximated by an ellipse with semiaxis dimensions of about 80 μm × 28 μm (see Fig. 3). The fluence F is (960 ± 170) mJ/cm². The uncertainty in F is dominated by fluctuations in the laser output intensity.

1. Understanding and quantifying the process: Laser ablation of polyimide

Laser ablation via ultraviolet radiation is an established method for the microstructuring of different polymers such as poly(ethylene terephthalate), polymethyl methacrylate, and polyimide. Since polyimide can easily be ablated with low-fluence pulses (100–300 mJ/cm²), we have selected this material as a suitable candidate for our low-end technical setup. The etching process is dominated by photochemical decomposition due to a multiphoton excitation process that causes photoreactions at the weak bonds in the imide groups.

For our experiments we use DuPont Kapton® 50HN sheets with a thickness of 12.5 μm, placed on standard microscope slides. A UV-fluorescent white paper sheet underneath the polyimide sample film allows us to determine the number of pulses that are required to fully ablate the sample. As soon as the fluorescence of the sheet becomes visible, the entire thickness of the Kapton has been ablated. By simply counting pulses until the fluorescence is visible, students can estimate the ablation rate which is found to be between 0.5 – 0.6 μm/pulse. Since UV-ablation is usually performed with excimer lasers at wavelengths of 193, 248, or 308 nm, our results cannot directly be compared to those reported in the literature. However, polyimide ablation rates between 0.4 and 0.6 μm/pulse at excimer-laser pulse fluences of about 1000 mJ/cm² have been reported before, and our results are thus consistent with established values. Figure 3 shows a photograph of a polyimide sheet after a single laser pulse has hit the sheet. We observe a characteristic soot-like halo of the ablation products around the laser-ablated spot. These ablation products mainly consist of oxides of carbon, HCN,
and elemental carbon. We conclude that photoablation processes in polyimide can be investigated by students using a simple homemade UV-laser in combination with a low-end microstructuring setup.

Nearly all measurements and calculations, such as laser power, pulse width, microscopic analysis, and fluence, can be carried out by the students. They will learn about the physics behind these parameters and gain experience in operating modern measurement instruments such as PIN diodes, power meters, and storage oscilloscopes.

2. Micromachining: Structuring patterns and images into permanent marker films

Although polyimide films are ideal for quantitative ablation experiments, they are less ideal for writing complex patterns while observing the process of micromachining. The relatively low ablation rate of polyimide leads to long processing times and the dark ablation products blur the observer’s vision onto the sample. We discovered that lines of ordinary permanent markers on standard microscope slides can be micro-structured quite easily with our setup. We have found that only a single pulse is required to make the entire area of the laser spot become transparent and that no disturbing products are blurring the vision. The resulting microstructures are very well defined with sharp edges and corners. Figure 5 shows microscope images of a laser ablated cube structure with an edge length of about 300 μm and a “House of St. Nick” with a total width of 400 μm that have been written into films of permanent text marker on standard microscope slides. These patterns can be written by high-school students with the help of our dedicated software tool that allows us to program the xy-plane stepping actuators (see Sec. III A) with arbitrary sequences. We would like to emphasize the enormous excitement and motivation which we observe every single time a team of students designs and manufactures their own microstructure.

An interesting scientific question is whether the transparency of the laser-treated sample areas is the result of a deactivation of the dyes in the markers or the result of an actual ablation process. To examine the sample areas in more detail, we have carried out atomic force microscopy (AFM) measurements. Using a contact-mode AFM, we have scanned the crossovers between the untreated film surface, a laser structured line, and—as a depth reference—a mechanical scratch in the film. We have determined the film thickness to be about 800 nm. The laser-structured line turned out to be an ablated groove in the film where a single pulse has been able to fully disintegrate the material down to the bottom of the film, i.e., the surface of the glass slide. The bottom and the edges of the mechanically generated scratch are very smooth while at the edges of the laser structured groove, ablation products with typical sizes around 100 nm are found.

Figure 6(a) shows the topography of a laser-ablated groove. The groove exhibits a width between 25 and 30 μm (x-direction) and is consistent with the width of the laser beam we have obtained via light microscopy (28 μm). In addition, the contour of the groove appears to be asymmetric. Figure 6(b) shows a projection of 200 scan lines, each with a length of 50 μm in x-direction, onto an axis perpendicular to the groove direction. This graph shows that the depth of the groove is close to 800 nm. We observe a rather steep slope on the left side of the groove, whereas the right side inclines

![Fig. 6. Topographic images of a laser ablated groove in permanent marker film. The images have been obtained with a contact-mode AFM. (a) Three-dimensional image of the ablated groove. (b) Cross-section of the groove (tilted data, 200 scan lines).](image)

![Fig. 7. (a) Diffraction grating with 10 lines. The spacing between individual lines is 50 μm. (b) Microscopic photograph of the diffraction pattern generated with the grating shown in the left panel. Both primary and secondary maxima are observed.](image)
more gently. This suggests that the sample film shows ablation along the full width of the laser spot, which is between 25 and 30 µm, but only a length of 12 microns could be fully ablated. We attribute this effect to the very asymmetric profile of the laser intensity in this particular direction. This conclusion is substantiated by the fact that this behavior is consistent along each of the 200 scan lines. The small peaks that are visible for \( x < 10 \) µm and \( x > 40 \) µm are due to ablation products. This supports the notion that an ablation process is responsible for the transparency of the sample. Using the measured groove profile we estimate that the ablation rate in the high-intensity regions of the laser spot is at least 800 nm/pulse. In addition, we can now establish why—in contrast to the case of polyimide discussed before—there are no ablation products that blur the observer’s vision: the 100-nm ablation particles are simply too small to be observed with an ordinary light microscope. Interestingly, the properties of the intensity profile of the laser spot can be inferred from the form of the ablated groove in the sample film.

3. Application: Structuring of diffraction gratings

An important application of microstructuring is the fabrication of diffraction gratings for spectrometers. With our setup, students can design optical gratings and fabricate them. With a cheap laser pointer, diffraction patterns can easily be observed and analyzed. The students can produce gratings with various numbers of lines and study the differences between them, such as the distance between interference maxima and the number of secondary maxima. For this purpose, the fundamental grating equations can be used. The wavelength of the laser pointer can be determined by applying the Bragg’s Law. Figure 7(a) shows a diffraction grating in a permanent marker film consisting of 10 lines with a line spacing of 50 µm, fabricated by high school students. The periodic bulges disturbing the vertical lines are due to asymmetries in the laser profile since a line is composed of single laser spots, with a profile shown in Fig. 3, that are pieced together in the vertical direction. The presence of these bulges results in an interference pattern that looks more like one originating from a crossed grating than from a linear grating. The pattern can be seen in Fig. 7(b). The bulges form some sort of “dotted” horizontal lines and contribute significantly to the interference pattern.

These applications of microstructuring introduce our students to modern laser fabrication principles and combine materials science (fluences and ablation rates) and basic physics (laser physics and diffraction gratings). 

IV. CONCLUSION

We have presented a simple low-cost laboratory setup of a microstructuring experiment with a homemade UV-laser. We have shown that microscopic patterns and images can be created via ablation in polyimide and permanent marker films. The structuring process works by means of direct laser writing and the corresponding positioning stage can either be controlled manually or by programming of motion sequences. With this setup, we have quantitatively investigated the ablation rate in polyimide and have obtained results that are consistent with those from the research literature. Furthermore, the ablation of permanent marker films delivers intriguingly smooth and rather complex microstructures and at the same time represents the cheapest and simplest sample material to be used for our experiments. We have obtained additional information on the ablation process and the laser beam intensity profile via AFM measurements.

As a result, insight into the technically highly relevant UV-microstructuring process can be provided at the high school level using a very easy-to-understand setup. With this setup, high school and undergraduate students have an opportunity for hands-on work by directly designing and fabricating complex patterns into sample films. As an application experiment, diffraction gratings can be designed, fabricated, and analyzed by the students.

Our low-end setup spans the entire spectrum, from demonstrating laser operation all the way to UV-based microstructuring.

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