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Rapid Prototyping of Metalenses using a Focused Beam

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Abstract

Metalenses offer an alternative to typical glass lenses possessing unique physical characteristics such as negative indices of refraction, that enables sub-diffraction limited focusing and lens uses. DuPont Kapton film, a cheap polyimide, may be altered to demonstrate these properties using individual unit cells to create alternating dielectric, inductive, and capacitive layers combined to produce a metalens. Current processes achieve unit cells with line widths as narrow as 15µm, expanding the frequency range of these lenses into the microwave spectrum. Our team seeks to find whether using a high-powered, focused laser beam, using pyrolysis, provides a viable rapid metalens prototyping procedure for even higher frequencies by producing lines thinner than 15µm. We designed a multiple-lens system to focus a 532 nm beam to a near diffraction limited spot size of 1-2µm. Matlab script controlled two Thorlabs Z825B Servos, a Lambda Sutter SC shutter system, and a Physike Instrument E-664 servo to automate the burn process. We controlled the incident power on the Kapton using a Thorlabs ½-λ plate and beamsplitter, monitored by a power meter. Since a tightly focused beam has an extremely short Rayleigh Range, we first conducted experiments to empirically optimize the focus of the beam and maximize intensity delivered to the Kapton. After finding the optimal focus, experiments conducted at different incident powers and shutter timings found an optimal combination of 13ms and 375mW, producing the smallest, carbonized spots our team found to date at 2.29µm. To prevent warping, which moves the Kapton out of the Rayleigh Range; we believe repeated spots are best to produce a composite, conducting line. Previous research on this project produced conducting lines that correlated strongly with the burn spot size, suggesting that conducting lines of less than 15µm are obtainable with continued work and our current system.

Keywords: Metalenses, Pyrolization, Kapton Polyimide

1. Introduction

Metamaterials offer an alternative to a typical glass lens. Using dielectric, inductive, and capacitive layers, Kapton tape, a polyimide film that can be easily and cheaply manufactured, may be altered to exhibit a negative refractive index. Differing from lenses of natural materials, metamaterial lenses are comprised of microscopic unit cells which may be independently engineered to achieve optical properties[1]. There are multiple proven methods to manufacture these metalenses such as super ink-jet printing, photolithography, and pyrolysis[2]. Pyrolysis, the most efficient method, has achieved unit cells with line widths, at the smallest, of 15µm,[2] where smaller dimensions allow for higher frequency light to be affected by the lens.

Laser pyrolysis provides an efficient and rapid fabrication method for these metalenses. Previously, carbonized polyimide films, such as Kapton tape, have been developed as sensor substrates. Previous research shows that carbonized polyimide lines demonstrate conductive properties[3]. While super ink-jet and 3-D printing present viable rapid prototyping methods, this paper investigates whether using a high-powered laser beam, focused to a small spot size using an optical lens system and pyrolysis, can provide a more efficient rapid prototyping procedure to produce lines smaller than 10µm in width. We also aimed to compare experimental results with theoretical predictions. It is possible to design a mask to carbonize lines with a laser, but these masks are inefficient and introduce more cost. We present the optical setup employed to pyrolize spots and lines into the Kapton, and report initial observations of both. Future study is planned to refine such an optical system to efficiently provide higher quality carbonized polyimide lines.

2. Methodology

A Coherent Verdi V-10 532nm laser provided the source to our optical system. Following this, a Sutter Instrument's Lambda SC shutter system supplied a mechanism to control burning time. After the shutter, a Thorlabs RSP1X15 ½ Wave Plate in conjunction with a Thorlabs 532nm polarizing beam splitter allowed us to easily modify the delivered power to the Kapton without adjusting the overall beam power. The beam splitter split the beams by polarizations, and using a Newport Model 1935-C thermal power meter, we were able to control the power delivered to the Kapton film as demonstrated in Fig. 1. To pyrolize lines thinner than 10µm, an optical system was required to focus the original beam to near diffraction-limited spot size. To do this, we designed a three lens system to expand, collimate, and then focus the beam. This process of expansion, collimation, and sharpening focuses a beam to a smaller spot size than with a simple two lens system, as seen by the equation that governs a focused spot size, $2W_0' = \frac{4*\lambda*f}{\pi*D}$. A wider incident beam results in a smaller focused spot size, so our design intended to use a bi-concave lens to expand the beam to approximately two inches in diameter. After expansion a two lens system then collimated the beam and focused it to a near diffraction-limited spot size. By utilizing ABCD matrices, the expanding, collimating, and focusing lenses were found to be of focal lengths $f = -150$mm, $f = 1000$mm, and $f = 50$mm respectively, as shown in Fig. 1, resulting in near diffraction- limited spot size was calculated to be less than 1 µm and measured by a profiler to be 8 µm (the manufacturer's specified limit for the model). Initially, the Kapton was suspended on two platforms and positioned by two Thorlabs Z825B Servos in the X-Y plane. A Physike Instrument E-664 LVPZT-Amplifier/Servo positioned the Kapton in the Z plane. To find the positioning for the exact focus for the beam, we placed a Thorlabs servo in the Z plane too, using the Physike Instrument cube to fine tune the focus. A Matlab script directed the respective positions of these blocks, and the shutter time. These systems were connected through Matlab's Data Acquisition capabilities in conjunction with a National Instruments USB 6002 analog to digital converter. The Matlab code allowed a fully automated control over the position of the Kapton and the timing of the shutter. Spots were analyzed using a Mitutoyo 50X/.55 lens microscope.

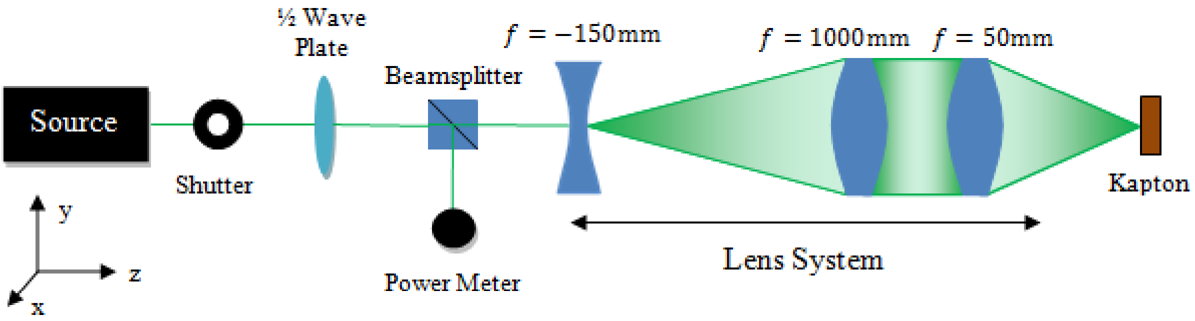

Figure 1: An illustration of the experimental setup. Following a shutter, the ½ wave plate, and the beam splitter, the beam is expanded, collimated, and focused to a spot by a bi-concave and two bi-convex lenses (focal lengths depicted above).

We characterized three main parameters: power, time, and focal distance. Majority of testing conducted aimed to find ideal conditions for the smallest spot size for pyrolization. The PI servo allowed micrometer control of the focal length from the 50mm lens. The automated Thorlabs servos provided for spacing between different samples to compare results and search for consistency among spots. Additionally, the Matlab control allowed for different timings and focal lengths to be tested while varying the power. Since a tightly focused beam has an extremely short Rayleigh Range, we first conducted experiments to empirically optimize the focus of the beam and maximize intensity delivered to the Kapton. The Thorlabs servo swept in .1mm intervals (its minimum resolution) through 8 to 10mm beyond the calculated focal distance of the final lens. After examining burns at these different intervals, the burns closest to the correct focus would actually be smaller, and surrounded by two very large burns. By narrowing down the best burn by finding these patterns, the PI servo swept through the .1mm interval 1µm at a time. We found the optimized burn at 8.893mm past the 11.1cm focus.

After maximizing intensity and the energy delivered to the Kapton, we tested to find the optimal power and timing. We determined these to be 375mW of power and 11-14ms shutter timing. In past research, difficulty to produce consistent results prevented taking the next step to burning lines. We thus conducted consistency tests and multi-burn tests. The consistency test simply took a specific power and timing and burned 10 spots, which were analyzed to find consistently small burns. The multi-burn test took $t = 13\text{ms}$ at a power of $\text{p} = 375\text{mW}$, and repeated ten spots three different times. The first iteration burned each spot once, the second twice, and the third thrice. Due to the difficulty in producing consistently small spots, this aimed to find an additional factor to producing consistency. In between burns, the program took a ten second pause to allow heat dissipation. Using the Mitutoyo 50X microscope we were able to observe and analyze the spots. By assuming the programmed distance between spots, we were able to approximate and scale the size of each spot.

3. Results

The results of the experiment produced the smallest spots seen to date, but still lacked consistency. While these sizes were approximated, a spot with a diameter of 2.29μm burned at our ideal parameters. Table 1 summarizes the results from varying timing:

t (ms)	11	12	13	14	15	16	17	18	19	20	21	22
r (μm)	6.11	9.92	8.39	16.03	32.1	18.32	13.74	25.95	8.4	20.01	19.08	24.43
t (ms)	23	24	25	26	27	28	29	30	31	32	33	34
r (μm)	5.34	16.79	53.43	9.92	10.69	11.45	6.11	19.08	26.72	13.74	12.98	11.45

Table 1: Diameters of spots in μm as timing increased

As seen above, timings of 11-14ms produced spots smaller than the 15μm threshold. Many spots though are significantly larger. We placed 500μm intervals vertically between each burn. We then conducted consistency tests at 375mW between 11 and 14ms per burn. As stated earlier, 13 ms was found to be the optimal shutter timing. At 14ms, spots would be too large, but at 11 and 12ms the spots would not fully pyrolize, leaving only a light indentation in the Kapton instead of a pyrolized burn. We found 13ms produced the best pyrolized burns, even though a few spots did not fully pyrolize. Of the 4 spots out of the 10 that did pyrolize, 3 were smaller than the 15μm threshold, and our smallest spot found to date at 2.29μm burned. These small spots are seen below:

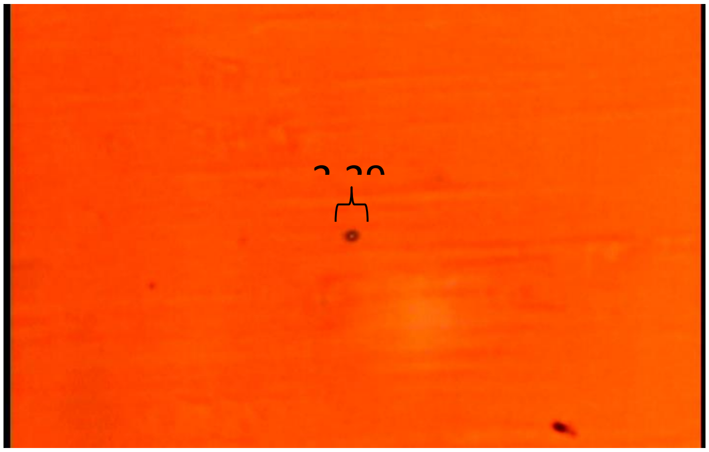

Figure 2: at 13ms and 375mW, this spot was sized at 2.29μm.

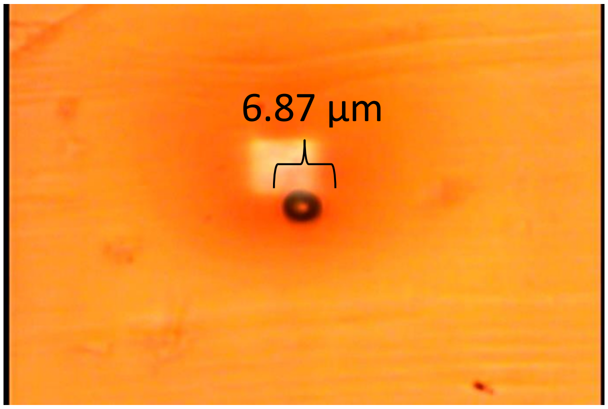

Figure 3: Sized at 11.45µm

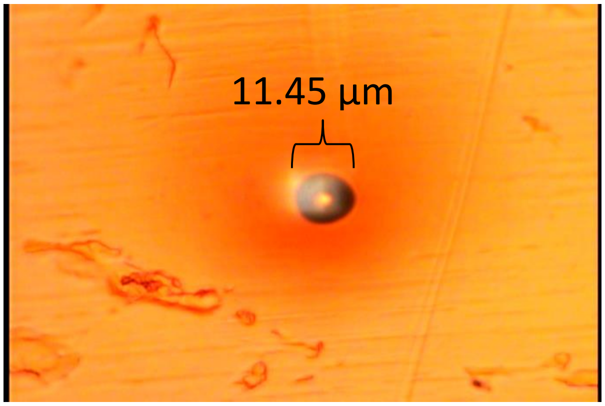

Figure 4: Sized at 6.87µm

Issues with the holding mechanism for the Kapton may have influenced these spots. When analyzing the depth of actual width of the Rayleigh Range, dictated by the $2z_0 = \frac{2\pi * W_0^2}{\lambda}$, where W_0 is the desired beam waist, λ is the beam wavelength, and z_0 is the width of the Rayleigh Range, $z_0 = 2.7\mu m$. With such a small Rayleigh Range, when the Kapton tape was inserted and tightened into place, a few things may have affected the results. First, the platform may have been pushed accidentally out of the focus by the tightening of the screws. Also, the actual mechanism may have failed to hold the Kapton perfectly flat. A slight bend in the Kapton tape could have easily moved a burn spot out of focus, affecting consistency of the burn spots. Additionally, the heat between the burns potentially may have warped the Kapton as seen in previous research from the summertime. This most likely contributed to the inconsistency seen.

The results of the variance test did not provide more burns than the parameter tests from the summer, but the burns we did have were very consistent. Only 3 spots burned in the n = 3 trial, and 2 in the n = 1, which accentuates the difficulty of producing small, consistent burns. But, all the burns were of consistent size, and all less than 16µm in diameter. For the burns, µ = 14.016µm and σ = 2.79µm. With a deviation of only 2.79µm, especially when aiming for such small spot sizes, our spots were consistent in size, showing that a method to consistently burn the Kapton tape could lead to burning lines.

4. Conclusion and Future Work

This paper investigated the viability of metalens prototyping using a focused beam. Our work found the proper focus point to maximize the intensity, which in future research allows flexibility between varying the timing and power. While we were unable to produce conducting lines thinner than the 15µm threshold, spots that were much smaller than the goal were found. Despite running into difficulty consistently producing burns, we did find consistent size from the burns that pyrolized the Kapton tape. The small sizes though are promising, and future research, if able to achieve consistent pyrolization, will be able to produce conducting lines smaller than 15µm.

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6. References

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