In order to advance the usefulness of polymer optics in practical applications, it is necessary to have a tool that can detect integrated optical elements and subsequently modify the polymer to network several elements. It is this project’s objective to create a tool that can detect a surface at one specific point in 3 dimensions, and additionally be able to modify the polymer at virtually the same 3 dimensional point.

Specifications

The photopolymer used requires two separate wavelengths of light to produce the desired results; red light (632.8 nm) can detect without modifying, while green light (532 nm) is used to “write” to the polymer. This bi-chromatic system introduces dispersion problems that need to be compensated for. In addition, the tool needs to be designed with resolution on the order of 10 microns or less. Specifications are as follows:

- Focused spot size of ~2 µm (for both colors)
- Resolution in the depth (z) direction of less than 10 µm
- The difference of foci of the two colors should be less than 2 µm (in the material)
- Focused spots should line up in an undetermined thickness of the material (not to exceed 1 mm)

Simply, the two spots have to be at the same place in the material, and the detection system must be accurate. An important point to note in the design of this system is that the two colors will not be on at the same time.

The cost limitations are undefined, as are the space limitations. Logically, it is better to use off-the-shelf lenses if at all possible, as well as confining space to that of a standard 4 by 8 foot table. However, these specifications are flexible.

Design Possibilities

There are two basic methods to determining the precise position of an embedded element in polymer: measure the transmission through the polymer or the reflection from the polymer. The confocal reflection microscope system provides an accurate feedback signal, its design will be further described in the next section. A transmission detection system is much less sensitive to minor index changes.
A major problem with the confocal microscope system is that its lenses are subject to dispersive effects. The green spot will focus at a point closer than the red spot.

Possible approaches to fix this problem:
1. Mirrors are achromatic. Is it possible to arrange a confocal microscope system that performs the same function as that shown above with mirrors only?
2. Change input collimation. Since the two beams that serve as an input to the system do not come from the same source, their individual collimation may be changed on one beam so that the convergence (focus) of each beam lines up perfectly with the other in the material.
3. Is there a creative cascade of lenses that can accurately “undo” dispersive effects?
4. Holographic lens. The photopolymer material is a very effective holographic material. Is it possible to make a lens out of it that focuses down to a very small spot? Using the unique abilities of the hologram, two holographic elements could be created for each lens, so that the red beam shines on to the hologram, and sees one lens with a specific focal length, and the green beam shines on the same hologram, but sees a lens with a different focal length. Could the effective focus for each beam be matched and to the correct size?
5. Can we effectively and accurately quantify the distance between the foci, and simply translate the material to compensate for the shift?

Each approach shall be discussed in turn.

1. The mirror idea would significantly reduce the chromatic aberrations of the confocal microscope system, but adds some complications, because it requires the system to be “folded” back on itself. This would demand a very creative solution in itself to align correctly. However, the small spot size listed in the specifications requires a very high NA, which translates to a very short focal length (exactly what that focal length is will be in the next section). This means a very curved lens, sitting very close to the material. A quick sketch on the back of an envelope shows that it is virtually impossible to angle a beam into the mirror while simultaneously hitting the polymer with only the focused light. Due to the difficulty of building a system contributes to the reduced ability for an effective system. This design is simply not practical for this situation.

2. Changing the collimation of the red beam so that it is already converging before it hits the short focal length lens has the effect of, in theory, placing the focus at a distance equal to that of the green beam.

![Figure 2 Chromatic Aberrations in a Confocal Microscope](image-url)
larger the pinhole, the lower the accuracy. A possible design would be to use separate pinholes for each beam. To do this, a beam splitter and two notch filters would be required on the return path.

![Confocal Microscope Corrected for Chromatic Aberrations](image)

This system certainly has potential, but it is not perfect. While the spots can be placed on top of each other, and the spot size is virtually the same (16 nm different), the dispersion of the material is not accounted for. Since both beams will travel a variable distance through the polymer, and the polymer has dispersive characteristics of its own, the spots will eventually separate. Additional methods must be employed to maintain the specifications throughout the entire polymer. If the system was optimized to match both spots half way through the polymer, it is possible the difference between the spots at either extreme falls within tolerance. This system should be further analyzed to ascertain its viability.

3. While a dispersive positive lens causes a green beam to focus at a shorter distance, and dispersive negative lens would have the opposite effect. It would cause the green beam to diverge at a greater angle. The question posed is if it would be possible to cascade several lenses together, both positive and negative, to achieve an effectively achromatic system. While it is conceivable, the net effect would be a change in the collimation of the beam incident on the short focal length lens. It is fundamentally the same as the previous design solution, with the exception that it would be significantly harder to implement.

4. The holographic optical element system offers answers to some problems that are not solved elsewhere. In this case, one would use a very high NA lens to make a very small spot size, and the spot would be focused a known distance behind a small piece of glass (preferably in polymer). The beam would be recorded in the standard way, with an angled coherent plane wave. The high NA lens would then be adjusted so that the other beam could be recorded onto the same material, in the same way, with the focused spot also in the same place. The reference beam would obviously match the color that was being recorded at the time. The small spot may be reconstructed by shining a conjugate of the reference beam, in other words, shine the light backwards and a spot will appear.
One of the greatest advantages to such a system is the focused spot could still be small, while the working distance of the “lens” would not be limited as with standard glass lenses. Additionally, aberrations are automatically compensated for. Unfortunately, the hologram does not have the capability to adjust for the variable depth of material encountered. Its only advantage over the previous (uncollimated) system is the ability to minimize optical system aberrations, such as spherical aberration. Major disadvantages include the hologram’s extreme sensitivity to movement and angle during both recording and reconstruction. Photopolymer is a natural choice for a recording material, but it is also quite sensitive to temperature variations.

5. Finally, simply taking advantage of the temporal separation between the colored beams, a straightforward solution would be to move a translation stage a specific distance to compensate for the focal shift due to dispersion. This distance would be most easily, and accurately, discovered by experimental data and curve fitting techniques. Also, theoretical calculations could be conducted concurrently to help determine the best curve to fit, as well as verify the consistency of the experiment. The major drawback to this approach is that calibration would need to be conducted on a regular basis, as well as new curves need to be determined as material composition is changed.

Based on these five design choices, the most interesting design to further explore is the one represented by Figure 3. It is not the most straightforward, nor does it correct for all types of aberrations, but it accomplishes the objectives of this design project.

Paraxial design:

Green is defined as $\lambda=532$ nm light, and red is defined as $\lambda=632.8$ nm.

One of the most limiting factors of the system is the small spot size; it is as good a place as any to start. We will need these two equations: (Where NA = D/(2F) )

Radius of a resolvable spot

$$\rho = \frac{0.6 \lambda}{NA}$$  

(1)

and Depth of Focus

$$\delta z = \frac{2.4 F^2 \lambda}{D^2}$$  

(2)

We are given that $\rho$ must be less than 2 $\mu$m, so therefore our NA must be .16 for green light, and .19 for the red light. This also means our $\delta z$ is 21 $\mu$m for the red light. This breaks our depth specifications, so therefore something needs to be changed. As $\delta z$ scales by the square of 1/NA, a little change there would quickly get the design into specifications. Doubling the NA to .38 will have the effect of decreasing the smallest resolvable spot to half that required, as well as decreasing the $\delta z$ to half that required.
Table 1 Paraxial Capabilities of the Corrected Confocal System with an NA of .38

<table>
<thead>
<tr>
<th></th>
<th>Red ($\lambda = 632.8\text{nm}$)</th>
<th>Green ($\lambda = 532\text{nm}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>.999$\mu$m</td>
<td>.84$\mu$m</td>
</tr>
<tr>
<td>$\delta z$</td>
<td>5.26$\mu$m</td>
<td>4.42$\mu$m</td>
</tr>
</tbody>
</table>

With an NA of .38, the F/D ratio becomes 1.316.

Looking ahead, it is easier to find a high NA lens that has a small focal length (the requirements on the physical size of the lens are much smaller). Therefore, I would choose a focal length that is approximately 4 mm. This translates to a lens power of 250 diopters.

If there is an index “bump” at the focus, it will reflect perfectly back through the lens, and the green light will be collimated as it travels back upstream, where it is differentiated from the red by a notch filter, and focused by a lens onto a pinhole. The lens system should be optimized so that significant light goes through the pinhole only when collimated light is the input of the lens. This means the pinhole will be at the focus of the lens.

Finding the prescription for this lens is a little less constrained. First, it should be able to have a fairly sharp response when a reflective surface is at the focal distance of the first lens so that high resolution is achieved. However, if it is too sharp, the pinhole size required for accuracy would be quite small. In addition, alignment would be much more difficult. The following paraxial spreadsheet analysis shows that a 100 mm focal length lens would have an acceptable resolution. To analyze this, only the reflected beam from the index “bump” is necessary. First, we have an exiting beam (reflected) at maximum NA corresponding to a slope of 2.63. It is shown that the final height is zero, in other words at a focus 100 mm past the lens. Note the focal length of the lens is adjusted for green light for comparison with the red beam later. All quantities are in meters or inverse meters.

Table 2 y-u Tracing for the Green Light Branch of the Corrected Confocal Microscope

<table>
<thead>
<tr>
<th>Surface 1</th>
<th>Angle</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.631579</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface 2</th>
<th>Angle</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.010452</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface 3</th>
<th>Angle</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.10452</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface 1</th>
<th>Curvature</th>
<th>Index</th>
<th>Length'</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0039719</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface 2</th>
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<th>Index</th>
<th>Length'</th>
<th>Power</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>251.7668</td>
<td>0.010452</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface 3</th>
<th>Curvature</th>
<th>Index</th>
<th>Length'</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>10</td>
<td>-0.10452</td>
<td>0</td>
</tr>
</tbody>
</table>
Here, we can see what the final output is at 100 mm if the reflective surface is 10 µm different.

Table 3 y-u Tracing for the Green Light Branch of the Corrected Confocal Microscope with a 10µm δz shift

<table>
<thead>
<tr>
<th>Surface</th>
<th>Curvature</th>
<th>Index</th>
<th>Length'</th>
<th>Power</th>
<th>Angle</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0039819</td>
<td>0</td>
<td>0</td>
<td>2.631579</td>
<td>0</td>
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<td>200</td>
<td>251.7668</td>
<td>251.7668</td>
<td>0.010479</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>10</td>
<td>10</td>
<td>13.13947</td>
<td>-0.00066</td>
<td></td>
</tr>
</tbody>
</table>

As long as the pinhole radius is less than .66 mm, there will be a significant drop in power if the reflective surface is more than 10 µm away from the focus of the first lens. Ideally, the pinhole should be approximately 1.5 or 2 times the size of the minimum spot size from the 100 mm lens to maximize resolution. Using the ABCD matrix approach, we can easily find the minimum spot size: (see code in Appendix A) $w_0=18.7\mu$m. Therefore a pinhole of 75µm is sufficient, and provides more than enough resolution.

The confocal branch for the red light should be optimized so that significant light goes through the pinhole only when there is an index “bump” at its focus. This pinhole will be at a position different than the focus of the lens. This once again is most easily analyzed using the spreadsheet method of y-u tracing, and only the reflection is analyzed. The focal lengths of the lenses are adjusted for red light.
With this branch of the system, the distance between lenses is important, and a somewhat realistic number of 2 meters was chosen. The physical layout of such a system may require an adjustment. When a 10µm δz shift is introduced, a pinhole size of 75µm will also be sufficient, though the tolerances are a little narrower. The ABCD calculated spot size is \( w_0 = 18.4 \mu m \).

With this paraxial system, all design specifications can be achieved. Since there are no quantifiable data on the dispersion of the material, it is impossible to determine exactly how far apart the spots are at an arbitrary position in the photopolymer. Also, the red beam incident on
the 4 mm lens must have the same angle on the way into the lens as it does on the way out, so therefore the beam must have a convergence angle of 0.027983.

Gaussian Design

The short focal length lens must go through a 1 mm slab of glass before it gets into the material. Therefore, it would be most advantageous to get a lens that can handle both large NA and correct for aberrations introduced by this glass. Lens 350340 in the Lightpath catalog matches nicely. The other two lenses were matched by design at 100 mm. The Linos catalog number 322288 matches the design specifications.

When thickening these lenses, the only interesting one is the Lightpath short focal length lens. The Linos lenses are in portions of the system where distance isn’t as critical, as well as having a long focal length. As a result, the $\delta$ distance of the principle plane from the surface of the lens represents a very small (< .1%) error in positioning on the table, one that is inconsequential in this system. The Lightpath lens introduces some interesting constraints. The working distance is only 1.56 mm, while the effective focal length is 4.03mm, giving a principle plane $\delta$ distance from the surface of 2.47 mm. This severely limits the total thickness of the material being written in (to less than 1.56mm). Working distance in this case includes the glass coverslip over the material.

Finite Design

With the exception of the specific dispersion of the material, this system accurately compensates for the inherent focal shift of this bi-chromatic system. It falls within specifications, and is reasonable easy to implement. The capabilities of this system include a spot size of less than 1 µm for each color, with a depth of focus of approximately 5 µm. The system’s sensitivity to reflective materials is smaller than 10 µm in both colors as well. Most importantly, the two focal points line up as long as the collimation of the red beam can be achieved with a tolerance of .5 micro radians. The obvious stop in this system is the pinhole at the end of the confocal microscope. It is both the aperture stop and the exit pupil. The entrance window is at infinity.
Figure 2 Final Finite Design
Appendix A  Matlab code used in Gaussian ABCD matrix design:

%input given values
% n = 1.5;
% R1 = .002;
% R2 = .001;
% l = 0.0005;

d = 0.0985:.000001:0.100;

%These are the values for 632.8 light
%f0=4.01462*10^-3;
%f1=99.6182*10^-3;
%n2=1.5055;
%d1=2.50912*10^-3;

%These are the values for 532 light
f0=3.97193*10^-3;
%f1=98.559*10^-3;
n2=1.5095;
d1=2.462427*10^-3;

format short e
d

%calculate q1
w1 = 850*10^-6;
lambda = 0.5*10^-6;

%Note: @ w1 R = infinity so there is only an imaginary term
invq1 = 0-i*lambda/(pi*w1^2);
q1 = 1/invq1;

%loop over several values for d to find smallest beam size aka: waist
for ct = 1:length(d)

M1 = [1 0;(-1/f0) 1]; %through 4 mm lens
M2 = [1 d1; 0 1]; %distance after lens
M3 = [1 0; 0 n2/1]; %air/glass boundary
M4 = [1 0.002; 0 1]; %through glass, against reflective surface, and back
M5 = [1 0; 0 1/n2]; %glass/air boundary
M6 = [1 d1; 0 1]; %distance to the lens
M7 = [1 0;(-1/f0) 1]; %through 4 mm lens again
M8 = [1 (f0+f1); 0 1]; %distance to next lens
M9 = [1 0;(-1/f1) 1]; %through 100 mm lens
M10 = [1 d(ct); 0 1]; %distance after lens (varied)

T1 = M10*M9*M8*M7*M6*M5*M4*M3*M2*M1;
T2 = [1 0.001; 0 1]*M3*[1 .002509+.000000001*ct; 0 1]*M1;

invq2(ct) = (T1(2,1)*q1 + T1(2,2))/(T1(1,1)*q1 + T1(1,2));
invqmat(ct) = (T2(2,1)*q1 + T2(2,2))/(T2(1,1)*q1 + T2(1,2));
w2 = sqrt(-lambda./(pi.*imag(invq2)));
wmaterial = sqrt(-lambda./(pi.*imag(invqmat)));

end
%fancy schmancy plots
subplot(2,2,1); plot(d, real(invq2)); %when this is 0 we are at the waist
subplot(2,2,2); plot(d, imag(invq2));
subplot(2,2,3); plot(d, real(w2)); %min is the waist
subplot(2,2,4); plot(d, imag(w2));
[Y, I] = min(real(w2))
[Y1 I1]= min(real(wmaterial))