Adjustable hybrid diffractive/refractive achromatic lens

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Abstract: We demonstrate a variable focal length achromatic lens that consists of a flat liquid crystal diffractive lens and a pressure-controlled fluidic refractive lens. The diffractive lens is composed of a flat binary Fresnel zone structure and a thin liquid crystal layer, producing high efficiency and millisecond switching times while applying a low ac voltage input. The focusing power of the diffractive lens is adjusted by electrically modifying the sub-zones and re-establishing phase wrapping points. The refractive lens includes a fluid chamber with a flat glass surface and an opposing elastic polydimethylsiloxane (PDMS) membrane surface. Inserting fluid volume through a pump system into the clear aperture region alters the membrane curvature and adjusts the refractive lens’ focal position. Primary chromatic aberration is remarkably reduced through the coupling of the fluidic and diffractive lenses at selected focal lengths. Potential applications include miniature color imaging systems, medical and ophthalmic devices, or any design that utilizes variable focal length achromats.

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1. Introduction

A traditional achromatic lens or achromat corrects for primary chromatic aberration by matching the focal points of a red and a blue wavelength. The dispersion is reduced over the visible spectrum, however residual secondary chromatic aberration remains at the green wavelength. Achromatic doublets consist of a crown glass followed by a flint. The crown glass has a positive focal length with low dispersion while the flint has a negative power with high dispersion. The combination of these two glass disparities is designed to match the red and blue wavelengths to a common focus along the optical axis (z-axis) to eliminate primary chromatic aberration.

It is known that diffractive lenses have strong chromatic aberration [1]. We have previously reported on designing and demonstrating adjustable focus diffractive lenses using liquid crystal as the variable index medium [2,3]. In this paper, we present an adjustable liquid crystal diffractive lens and an adjustable pressure-controlled fluidic lens in combination (Fig. 1) minimizes primary chromatic aberration. Previously, discrete tunable liquid crystal diffractive lenses [2–6], continuous tunable liquid crystal refractive lenses [7–9], and continuous tunable fluidic lenses [10–12] with variable focal lengths were demonstrated individually. At each focal location chromatic aberration is observable when uncorrected. Chromatic aberration is greater in elements with larger dispersion, such as diffractive lenses, and becomes more significant for materials with lower Abbe numbers. Diffractive and holographic lenses have been proposed to replace the traditional achromatic doublets for fixed focal length designs [1,13]. More recently, a useful hybrid variable focal length fluidic/diffractive lens was demonstrated; however, the diffractive component applies a fixed focal length [14]. We have extended this work to include a variable focal length diffractive component. In effect, we have created a variable achromatic doublet with no moving parts.

Diffractive lenses have an Abbe number much smaller than their refractive counterparts [1]. The Abbe number of a diffractive lens is unique in that it is equal to -3.45, solely dependent upon the specified Fraunhofer d, F, C wavelengths, as given by $V_{\text{diffractive}} = \lambda_d f / (\lambda_F - \lambda_C)$ [1,13]. The focal length of a Fresnel zone-based diffractive lens is given by $f = r_1^2 / (2 \lambda)$ where $r_1$ is the radius of the first Fresnel zone and $\lambda$ is the wavelength of the incident light [1]. Therefore, the focal length at any other wavelength $\lambda$, in nm, can be scaled by the design wavelength according to $f(\lambda) = (555/\lambda) f_d$ where $f_d$ is the design focal length at 555 nm.

An approach must be established to correlate the diffractive lens with the refractive lens. For certain focal lengths of the diffractive lens, $f_d$, we may choose the focal lengths and Abbe number of the fluidic lens such that they satisfy the achromat equation: $f_d V_f - 3.45 f_d = 0$, where $f_d$ and $V_f$ are the focal length and Abbe number of the fluidic lens, respectively. Refractive lenses have an Abbe number that is related to the indices of refraction as specified by the Fraunhofer d, C, F lines where $V_{\text{fluidic}} = (n_d - 1) / (n_F - n_C)$. By knowing the focal length of the diffractive lens and the Abbe numbers of the refractive and diffractive lenses, one is able to determine the focal length range of the fluidic lens required to achieve an achromat. Table 1 identifies which focal length ranges are necessary for a variable fluidic lens to...
produce an achromat with diffractive lenses ranging between 67 mm and 1000 mm focal lengths at specified Abbe numbers of the refractive lens. Optical glasses have an Abbe range between 25 and 65 [15], however using optical fluids increases this range of achievable Abbe numbers. Once the focal lengths are determined to identify what is necessary to match the diffractive lenses, the proper Abbe number and hence fluid may be chosen to achieve this goal.

2. Liquid crystal diffractive lenses

We began by designing diffractive elements with known focal lengths and Abbe numbers. We developed two variable focal length diffractive lenses. Diffractive lens A possesses a design focal length of 1000 mm at $\lambda = 555$ nm with a clear aperture of 10 mm and eight binary phase quantization that results in a maximum diffraction efficiency of 94.9% in theory. Diffractive lens B possesses a design focal length of 400 mm at $\lambda = 555$ nm with a clear aperture of 6 mm and twelve levels of binary phase quantization that results in a maximum diffraction efficiency of 97.7% in theory. By properly shunting the electrodes, the diffractive lens A can provide focal lengths of 1000 mm, 500 mm, and 250 mm, and the diffractive lens B can provide 400 mm, 200 mm, 133 mm, 100 mm, and 67 mm focal lengths [2,3].

Desired phase profiles are achieved by shifting the effective refractive index of a nematic liquid crystal. The nematic liquid crystal is sandwiched between a flat Fresnel zone electrode substrate and a ground reference substrate, where both substrates contain a transparent and conductive Indium-Tin-Oxide (ITO) layer. To maintain the electrical isolation between the electrodes in the diffractive lens A, the odd-numbered and even-numbered electrodes are formed in two separate layers with an insulating layer of SiO$_2$ in between [3]. For the diffractive lens B, one-micron gaps are implemented as isolators between the electrodes that reduce the fabrication steps [2]. The electrodes (or subzones) of the same counting index within each of the Fresnel zones are connected to bus bars through vias made in the insulating layer of SiO$_2$.

Fabrication of our diffractive lenses involves a few steps of deposition, lithography and etching. Ion beam sputtering was the deposition method used to produce uniform films of around 150 nm thick. Then photo-lithography was carried out using a diluted S-1805 photoresist (from Rohm and Hoss) and Karl-Suss MA6 mask aligner. The patterns were then etched using the appropriate acids/etchants for each layer. After the micro-fabrication process, both the patterned electrodes and the reference substrates are spin-coated with a nylon alignment layer. The substrates are then baked at 115 °C, buffed unidirectionally, and put together in the anti-parallel geometry to provide a homogeneous molecular orientation for the liquid crystal. Glass fiber spacers are used in the cell assembly. The lens cell is filled with the liquid crystal (E7 from Merck) via the capillary action at a temperature above the clearing point (60°C) and cooled slowly to the room temperature. Finally, the cell is sealed and connected to drive electronics through a set of thin stranded wires.

Two resistive circuits with eight and twelve potentiometers drive the diffractive lenses. The resistances and the input voltage, hence the driving electric field across different Fresnel subzones, are adjusted to introduce the appropriate phase shift for the maximum diffraction efficiency. The voltages are applied simultaneously and are monotonically increasing from the first to the last subzone. The focal lengths are electronically switchable to fractions of the maximum design focal length in milliseconds. It is also possible to achieve negative focal lengths by reversing the order in which the voltages are applied to the diffractive lenses, thus reversing the slope of the phase profile [2,3].

3. Fluidic refractive lens

The refractive lens is a plano-convex singlet with a predetermined amount of fluid inserted into the lens chamber. During preparation, fluid is inserted in excess within the chamber as to induce a vacuum pressure to evacuate air. If the air is not evacuated then it is treated as a second index within the clear aperture, resulting in a drastic alteration of desired lens
properties. Only the membrane curvature changes when fluid is pumped into the chamber since the frame is metal and the opposing side is transparent glass.

The deformable membrane layer is a moldable optically clear elastomer with uniform thickness. Fabrication of the deformable membrane involves a pre-backing process while the PDMS mixture is formulated within molds designed on a flat 5 λ glass surface. The mixture is deposited within the molds which are then stirred within a vacuum system as to remove the excess air within the PDMS. The thickness of the membrane depends on the amount of material deposited within each mold. After the air is evacuated, the PDMS is placed into an oven at 90° C for an hour. We then remove the PDMS and peel off the membrane layers, which have a designed thickness of approximately 30-120 microns [12]. The membrane layers are removed with nylon tweezers and trimmed to remove excess material. Removal of excess material is necessary as to ensure a flat membrane to be clamped into the chamber.

The chamber is a metal frame which the membrane locks into, possessing a clear aperture within the center and flanges on its periphery. Control of the lens’ output shape is achieved by controlling the clear aperture’s opto-mechanical shape, where this clear aperture has a circular shape as to produce a rotationally symmetric fluidic lens. There is a retainer ring that has equal and opposite flanges relative to the metal frame. Through pressure, the membrane is applied onto the flat metal frame and the retainer ring locks the membrane onto the frame. This flat frame is then aligned and squeezed into a two part assembly, creating the singlet chamber. The chamber is then mounted onto a frame that has openings to place onto a rail. The chamber poses a single fluidic fitting that connects the fluid chamber to a syringe.

A syringe is placed into a pump system that alters the fluid output, permitting for control of the fluidic lens’ radius of curvature and focal length. The applied pump controllers operate at a maximum of 0.0125 ml / sec, an operation rate of 50 µl in 4 seconds. This corresponds to a focal shift of approximately 10 mm per 50 µl evacuation when there is high lens curvature, and a shift of approximately 50 to 100 mm per 50 µl evacuation. The boundary between high curvature and low curvature varies with the designed focal length. With our fluidic chamber, which was designed for an 80 mm base focal length with methanol, an evacuation of 150 µl defines our barrier between low curvature and high curvature. It is observed in Fig. 4 as the approximate location in which the slope varies in the relative amount of fluid evacuated. Due to drastic fluid removal effects at flatter curvatures, it was opted to decrease the amount of fluid inserted or removed at higher radii of curvature. A plano-convex lens is developed over this region and only positive focal lengths are selectively outputted.

4. Methods and test results

It is non-trivial to place the proper fluid into the chamber when compensating for the diffractive lens. Identifying the proper fluid came from a four step process. Firstly, one must identify the membrane’s radius of curvature range. This allows for one to physically characterize the limitations of the fluidic lens. Also, by identifying the radius of curvature with a known fluid, it is possible to quantify the focal length range of any fluid by knowing the new fluid’s index of refraction. Once one knows the achievable radii of curvature and focal lengths of the fluidic lens, it is necessary to specify the focal lengths needed to compensate for the diffractive lens. For our experimental setup, we have already specified the Abbe number of the diffractive lenses and also the focal lengths achievable by our diffractive lenses. Table 1 took these values into consideration and found the focal length solutions of fluids at a wide scope of Abbe values. Therefore, we match the physical focal length range of the fluidic lens to a reasonable Abbe number so that a high percentage of achromatic doublets are achievable. The final step is to identify a fluid with the proper index of refraction and Abbe number as was previously assessed. It is also important that the fluid found is non-reactive or absorbive with the membrane that one is applying. Through this approach we satisfy the achromat equation: \( f_1 V_1 + f_2 V_2 = 0 \), where \( V \) is the Abbe number.
wavelengths or to concurrently test multiple wavelengths as shown in Fig. 2. The dichroic axis. The combination of the lasers allows to either individually test the lenses with specific with the previously described pump controls. All three laser beams were aligned to the optical

DI water has an Abbe number of 55.74 and the indices of refraction are known for a wide scope of wavelength ranges [16]. The focal lengths of the DI water fluidic lens were first measured using red (HeNe 633 nm), green (HeNe 543 nm), and blue (Argon 488 nm) lasers

Table 1. Values Needed for Fluidic Lens Focal Lengths \( f_g \) (in mm) at Different Fluid Abbe Number Values and Given Diffractive Lens Focal Lengths at the Design Wavelength of 555 nm

| Diffractive lens powers and focal lengths | Needed \( f_g \) if \( V_f = 5 \) | Needed \( f_g \) if \( V_f = 10 \) | Needed \( f_g \) if \( V_f = 13.66 \) | Needed \( f_g \) if \( V_f = 15 \) | Needed \( f_g \) if \( V_f = 20 \) |
|-----------------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1 D (1000 mm)                          | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 2.0 D (500 mm)                         | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 2.5 D (400 mm)                         | 276.00                       | 276.00                       | 276.00                       | 276.00                       | 276.00                       |
| 4.0 D (250 mm)                         | 172.50                       | 172.50                       | 172.50                       | 172.50                       | 172.50                       |
| 5.0 D (200 mm)                         | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 7.5 D (133.33 mm)                      | 72.00                        | 72.00                        | 72.00                        | 72.00                        | 72.00                        |
| 10 D (100 mm)                          | 69.00                        | 69.00                        | 69.00                        | 69.00                        | 69.00                        |
| 15 D (66.66 mm)                        | 46.00                        | 46.00                        | 46.00                        | 46.00                        | 46.00                        |
| 20 D (50 mm)                           | 34.50                        | 34.50                        | 34.50                        | 34.50                        | 34.50                        |
| 25 D (40 mm)                           | 27.60                        | 27.60                        | 27.60                        | 27.60                        | 27.60                        |
| 30 D (33.33 mm)                        | 23.00                        | 23.00                        | 23.00                        | 23.00                        | 23.00                        |
| 35 D (28.57 mm)                        | 19.71                        | 19.71                        | 19.71                        | 19.71                        | 19.71                        |
| 40 D (25 mm)                           | 17.25                        | 17.25                        | 17.25                        | 17.25                        | 17.25                        |
| 50 D (20 mm)                           | 13.80                        | 13.80                        | 13.80                        | 13.80                        | 13.80                        |
| 60 D (16.66 mm)                        | 11.50                        | 11.50                        | 11.50                        | 11.50                        | 11.50                        |
| 1 D (1000 mm)                          | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 2.0 D (500 mm)                         | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 2.5 D (400 mm)                         | 276.00                       | 276.00                       | 276.00                       | 276.00                       | 276.00                       |
| 4.0 D (250 mm)                         | 172.50                       | 172.50                       | 172.50                       | 172.50                       | 172.50                       |
| 5.0 D (200 mm)                         | 138.00                       | 138.00                       | 138.00                       | 138.00                       | 138.00                       |
| 7.5 D (133.33 mm)                      | 72.00                        | 72.00                        | 72.00                        | 72.00                        | 72.00                        |
| 10 D (100 mm)                          | 69.00                        | 69.00                        | 69.00                        | 69.00                        | 69.00                        |
| 15 D (66.66 mm)                        | 46.00                        | 46.00                        | 46.00                        | 46.00                        | 46.00                        |
| 20 D (50 mm)                           | 34.50                        | 34.50                        | 34.50                        | 34.50                        | 34.50                        |
| 25 D (40 mm)                           | 27.60                        | 27.60                        | 27.60                        | 27.60                        | 27.60                        |
| 30 D (33.33 mm)                        | 23.00                        | 23.00                        | 23.00                        | 23.00                        | 23.00                        |
| 35 D (28.57 mm)                        | 19.71                        | 19.71                        | 19.71                        | 19.71                        | 19.71                        |
| 40 D (25 mm)                           | 17.25                        | 17.25                        | 17.25                        | 17.25                        | 17.25                        |
| 50 D (20 mm)                           | 13.80                        | 13.80                        | 13.80                        | 13.80                        | 13.80                        |
| 60 D (16.66 mm)                        | 11.50                        | 11.50                        | 11.50                        | 11.50                        | 11.50                        |

De-ionized (DI) water was first used to characterize the fluidic lens’ radius of curvature range. DI water has an Abbe number of 55.74 and the indices of refraction are known for a wide scope of wavelength ranges [16]. The focal lengths of the DI water fluidic lens were first measured using red (HeNe 633 nm), green (HeNe 543 nm), and blue (Argon 488 nm) lasers with the previously described pump controls. All three laser beams were aligned to the optical axis. The combination of the lasers allows to either individually test the lenses with specific wavelengths or to concurrently test multiple wavelengths as shown in Fig. 2. The dichroic...
Mirrors have specified bands in which they reflect and transmit. We found the proper dichroic mirrors to pass the previous wavelengths while reflecting the incoming perpendicular laser wavelengths. By mixing the lasers or adding an aperture stop, we varied the desired input wavelengths. We then used a single beam expander using an achromatic objective lens and another achromatic collimating lens to collimate the three beams in this single optical axis. A color CCD camera on a rail was employed to find the best focus spot. The spots were not of a perfect sphere since there was a slight amount of astigmatism observed at the focal spot. This is caused by a slight distribution in tension around the flanges and it is observed more drastically at longer focal lengths.

As was previously stated we applied DI water, with known indices of refraction per wavelength, in identifying the fluidic lenses radius of curvature range. For a given amount of fluid in the lens, we measured the focal length at each of the three test wavelengths. The radius of curvature, \( r \), of the lens surface was calculated using

\[
\Phi = \frac{1}{f} = \frac{n_{\text{air}} - n_{\text{DI}}}{r},
\]

where \( \Phi \) is the surface power and \( n_{\text{air}} \) and \( n_{\text{DI}} \) are the indices of refraction for air and DI water per index, respectively. It is noted that with the defined coordinate system the radius of curvatures are negative values as the vertex to the center propagates to the left; however, we are stating the values as definitions of magnitude as to alleviate the constraint of a coordinate system. The index of refraction for air is approximately one at all wavelengths and the index of refraction of DI water is known at each wavelength [16]. The focal length, \( f \), of each measurement was equal to the back focal distance of the fluidic lens using the thin lens approximation. Each radius of curvature was calculated at red, green, and blue wavelengths and averaged to determine a single radius of curvature per fluid volume. The experiment was repeated as we increased the fluid volume in the lens by increments of 50\( \mu \)L.

To define the workable range for the fluidic lens we quantified the repeatability of outputting the radius of curvature. It was found that the average radius of curvature per fluid volume between the three wavelengths varied in accuracy of 0.02% to 0.88% for a radius of curvature from 20 to 100 mm. For DI water this corresponded to a focal length range of 60 mm to 300 mm. To clarify, a radius of curvature with an accuracy of 0.02% means that our lens accuracy for a radius of curvature at 20 mm was at 20 mm \( \pm 0.004 \) mm or with an accuracy of 0.88% the radius of curvature outputted at 20 mm \( \pm 0.176 \) mm. Similarly the radius of curvature range for our larger 100 mm varied from 100 mm \( \pm 0.02 \) mm to 100 mm \( \pm 0.88 \) mm respectively. It was found that the smaller radii of curvature actually observed a lower amount of inaccuracy. As we increase the amount of fluid we are reducing the lenses radius of curvature. This suggests that our caustic is not as long and more of the rays are focused in one location. What is occurring is that with a smaller radius of curvature we have almost no effect by the frame which allows for the shape of the membrane to be controlled by the fluid with almost no dependence on the opto-mechanical structure. With this higher control the smaller the radius of curvature the higher control of aberrations is observed.

We broke up the accuracy of the radius of curvature into two additional sections. The radius of curvature between 100 to 200 mm had outputted an accuracy between 1 and 2%,
which for DI water is a focal length range of 300 to 600 mm. Focal lengths from 600 to 900 mm produced an accuracy on the radius of curvature between 2 and 5% of the expected focal length. Our goal was to apply a highly accurate fluidic lens to couple with the diffractive lens as to diminish in accuracies related to the control of the fluidic lens. These two additional sections had high accuracy and repeatability but were not the best results since they had larger radius of curvatures. Therefore, we defined the highly accurate radius of curvature range between 20 to 100 mm as the fluidic lenses functional range while attempting to determine the best fluid to work with in producing the final achromatic design.

The two most significant fluid characteristics for this experiment, as was observed from the achromat equation, were the fluids focal length and Abbe number. The focal length is dictated by the radius of curvature of the fluidic lens and the index of refraction of the fluid. In the previous paragraph we experimentally assessed the fluidic lenses controlled radius of curvature range to be between 20 to 100 mm with high accuracy. The fluids index of refraction can vary the focal length, but the range would increase or decrease the focal range slightly. This is observable by evaluating $\Phi = 1/f = (n_{e\text{w}r} - \Phi_{FL})/r$ once more, where now $n_{FL}$ is the new fluids index of refraction rather than DI water. We observe that our only alteration to the equation is the applied fluids index of refraction. If we find a fluid with a larger index of refraction than the tested DI water, then focal lengths shorter than 60 mm are achievable. As most indices of refraction for glass range between 1.3 and 2.5, a reasonable approximation is that a majority of optical fluids operate within this index range. It is safe to approximate that the calculated focal length range of DI water of 60 mm to 300 mm can be decreased by at least 10 mm to 50 mm or higher. We are not stating that the focal length cannot be further decreased, but rather we are defining a reasonable index of refraction range as to not constrain the fluids when attempting to find the proper Abbe number to produce a functional diffractive / refractive achromatic lens.

With the focal length range approximated it was necessary to determine the proper fluid Abbe number to achromatize the focal lengths of the diffractive lens. On the left hand side of Table 1 are the diffractive lens values that would be required to be achromatized. Table 1 identifies which focal lengths are needed from the fluidic lens for each Abbe number to achieve achromatization with these designed diffractive lens powers. Our approximation showed that our fluidic lens will achieve focal lengths in the relative area of 50 mm or higher. Our experimental DI water has an Abbe number of 55. It is seen within the table that DI water would only achromatize the 1 D Diffractive lens with our fluidic lens, due to the constraints on the lenses radius of curvature. A fluid with an Abbe number of 15 would achromatize four of the diffractive lens’ focal lengths and an Abbe number of 10 would achromatize five focal lengths above 50 mm. Theoretically, a fluid with an Abbe number of 5, as observed from Table 1, would produce approximately all possible achromatic combinations from either diffractive lens developed here, since the greatest Diopter range achieved by the diffractive lenses is 15 D. Thus, finding a fluid with known indices of refraction to achieve a focal length as low as 50 mm and a characterized Abbe numbers from 5 to 15 offers the capability of illustrating a variable focal length achromat.

Methanol (Methyl alcohol) was chosen as the fluid for the fluidic lens due to its high dispersion value and non-reactivity with the PDMS membrane. Methanol has an Abbe number of 13.66 which achromatizes 5 of the diffractive lens focal lengths as is observed in Table 1 and is widely available as it is a cleaning agent. The desired focal length range to achromatize all of the diffractive lenses focal locations with the fluidic lens would be from 16.8 to 101.0 mm when coupled with diffractive lens B and from 63.14 to 252.6 mm when coupled with diffractive lens A. As was previously stated, the diffractive lens A provides focal lengths of 1000, 500, and 250 mm, and the diffractive lens B provides 400, 200, 133, 100, and 67 mm focal lengths. As seen from Table 1, all three possible focal lengths of the diffractive lens A, and two out of five focal lengths of the diffractive lens B (400 and 200) can be achromatized. Using Table 1, we identify the focal lengths of the fluidic lens for every focal length of the diffractive lens. Results of the two combined focal lengths develops a predicted achromatic focal length at green wavelength through $\Phi_{expected} = \Phi_{differential} + \Phi_{fluidic}$ and $expected = 1/
The five expected achromatic focal lengths, $f_{\text{expected}}$, for green must be achieved through the experimental setup for the achromat to work properly.

Focal lengths of the diffractive and fluidic lenses were first measured separately using the red (HeNe 633 nm), green (HeNe 543 nm), and blue (Argon 488 nm) lasers. We used a linear polarizer with the diffractive lens to account for the polarization effects of the nematic liquid crystal. We can remove the polarizer so the lens works with any randomly polarized light if we add another liquid crystal diffractive lens with an orthogonal buffing direction to the first diffractive lens. As expected, the red light comes into focus first for the diffractive lens since it has negative dispersion. The test results for the two diffractive lenses are shown in Table 2 and 3. The experimental and theoretical values of focal lengths at the aforementioned three test wavelengths are presented in Table 2 (diffractive lens A) and Table 3 (diffractive lens B). The design wavelength for both lenses is $\lambda = 555 \text{ nm}$, and the design focal lengths (1000 mm for lens A and 250 mm for lens B) as well as additional observed focal lengths developed when these lenses were shunted as is presented at the design wavelength. The focal lengths at the three test wavelengths are calculated using the diffractive lens formula discussed in the introduction, $f(\lambda) = (555/\lambda) f_d$ where $f_d$ is the design focal length at 555 nm.

| Wavelength (nm) | $f$ (555nm) = 1000 mm | $f$ (555nm) = 500 mm | $f$ (555nm) = 250 mm |
|-----------------|-----------------|-----------------|-----------------|
|                 | Data | Theory | Data | Theory | Data | Theory |
| 633             | 870  | 876.8  | 435  | 438.4  | 217  | 219.2  |
| 543             | 1015 | 1022.1 | 505  | 511.1  | 252  | 255.5  |
| 488             | 1125 | 1137.3 | 560  | 568.6  | 281  | 284.3  |

| Wavelength (nm) | $f$ (555nm) = 400 | $f$ (555nm) = 200 | $f$ (555nm) = 133 | $f$ (555nm) = 100 | $f$ (555nm) = 67 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Data | Theory | Data | Theory | Data | Theory | Data | Theory | Data | Theory |
| 633             | 354  | 350.7  | 174  | 175.3  | 116  | 116.9  | 88   | 87.7   | 59   | 58.4   |
| 543             | 405  | 406.5  | 202  | 204.2  | 135  | 136.1  | 102  | 102.1  | 69   | 68.1   |
| 488             | 447  | 454.9  | 225  | 227.5  | 152  | 151.6  | 114  | 113.7  | 76   | 75.8   |

As an example, the images of three of the focal spots of the diffractive lens B are shown in Fig. 3. This was for the case when the diffractive lens B was shunted from a 12-level lens to a 4-level lens in order to produce the focal length of 133 mm (at the design wavelength of 555 nm) which is one-third of the design focal length of 400 mm [2]. The focus spots were all nearly round and sharp, with some background scattered light due to lowering of the diffraction efficiency especially at shorter focal lengths.

![Sample images of the best focus spots for the diffractive lens B when it is set to the focal length of 133 nm at the green wavelength.](image)

The fluidic lens illustrates a nonlinear response as fluid is withdrawn. As the membrane reaches higher radii, the membrane becomes flatter. The sensitivity to the amount of fluid increases within this range since a smaller amount of fluid varies the curvature. The measured
values of the fluidic lenses focal length for the three wavelengths are depicted in Fig. 4 in terms of the amount of fluid injected in the lens.

![Fig. 4. Chromatic dispersion of the variable focal plano-convex lens alone applying methanol at the three test wavelengths when set for 80 mm focal length and higher.](image)

The final step in producing the variable focal length achromat is the combination of the liquid crystal diffractive lens with the pressure controlled methanol fluidic lens. After adjusting the focal lengths of each lens to the appropriate values dictated by the achromat equation we measured the overall focal length of the hybrid lens at the red, green, and blue wavelengths. The experiment verified that the focus spots of the red and blue wavelengths coincided very closely. Figure 5(a)–5(e) depict the focal spots for the red and the blue wavelengths as the focal lengths of the diffractive and the fluidic lenses are varied according to the achromat equation. In Fig. 5(a)–5(c) diffractive lens A, and in Fig. 5(d) and 5(e) diffractive lens B was combined with the fluidic lens. The other three focal lengths from the diffractive lens B could not be used for this experiment because of the limited minimum achievable focal length of the fluidic lens in its current form. As the focal length is decreased, the spot size and aberrations are reduced as expected; however, the background scattered light is slightly increased. This is caused by the reduction in diffraction efficiency at the shorter focal lengths as the number of binary phase levels decreases due to the electrode shunting [2,3]. The issue of low diffraction efficiency can be overcome by designing diffractive lenses with higher number of binary phase levels which results in smaller electrode sizes if the design optical power and aperture size are kept constant. This will require a more advanced micro-fabrication technique. On the other hand, the fluidic lens showed nearly round and sharp focus spots at short focal lengths when the curvature of the membrane was high, but at long focal lengths as the membrane became flatter considerable aberrations started to show up, of which astigmatism and coma were more pronounced as evident from Fig. 5(a) and 5(b).

Figure 5(f) shows the values of the overall focal length of the hybrid diffractive/fluidic lens for the green, blue and red test wavelengths. As expected, the green light comes to focus first and then the red and blue lights will come into focus near the same plane. The measured focal lengths of the hybrid lens closely matched with the expected focal length values seen from Fig. 5(f). Although our hybrid diffractive/refractive lens has the advantage of being multi-focal and non-mechanical compared to the traditional lenses, its current optical qualities are slightly inferior to the conventional lenses because of the few available focal lengths of our liquid crystal diffractive lenses in their current form and low diffraction efficiencies at shorter focal lengths, as well as physical limitations of our fluidic lens in its current form including small fluid pump, limited aperture size, and significant aberrations at longer focal lengths when the membrane’s curvature is decreased. The chromatic aberration was
significantly reduced but not completely at this time corrected due to the current limitations which can be overcome by improving the fabrication.

The clear aperture of our liquid crystal diffractive lenses is limited by the photolithography capabilities, number of binary phase levels, and diffraction efficiency, whereas the fluidic lens is aperture limited by the pressure control of the mechanical flanges on the periphery. If the aperture becomes too large then we cannot produce an even distribution of pressure holding down the membrane, inducing uncontrollable aberrations. The function radius of curvature of the fluidic lens is limited by the tensile strength of the designed membrane. Using a broad-band positive photoresist (S1805) and Karl-Suss MA6 contact printer operating around i-line (365 nm), we were able to achieve one micron feature sizes. Employing more advanced fabrication tools smaller features can be made and the design aperture can be increased. This is due to the facts that the Fresnel zones get narrower as moving away from center and as the number of binary phase levels or the design optical power is increased. Diffraction efficiency can also become a limiting factor if the zone widths become comparable to the liquid crystal thickness or the inter-electrode gaps (in case of one-layer electrode design) [2,3,17].

Diffractive lens A has a maximum design aperture of 10 mm, 8 phase levels, 1 diopter minimum optical power, no inter-electrode gaps (odd and even electrodes interleaved into two layers), about 8-micron narrowest electrode, and about 7-micron thick liquid crystal. Diffractive lens B has a maximum design aperture of 6 mm, 12 phase levels, and 2.5 diopter minimum optical power with one micron inter-electrode gaps (one-layer electrode design), about 5-micron narrowest electrode, and about 4-micron thick liquid crystal. To increase the diffraction efficiency, liquid crystal thickness can further be decreased by using smaller glass fiber spacer beads during assembly. However, the minimum thickness in order to achieve at least 2π phase retardation using the E7 liquid crystal and any wavelength shorter than 633 nm would be \(\frac{\lambda}{\Delta n_{\text{max}}} = \frac{0.633}{0.225} = 2.8 \text{ micron.}\)
In conclusion, we have demonstrated a variable focal length achromatic lens that consists of a variable liquid crystal diffractive lens and a variable pressure-controlled fluidic lens. We used two diffractive lenses that produce multiple discrete focal lengths with an Abbe number of −3.45. The fluidic lens can provide a more continuous variation, and its focal lengths are chosen such that they minimize the dispersion of the diffractive lens. We chose Methanol for the fluidic lens due to its high dispersion properties. Then we combined the fluidic lens and one diffractive lens at a time to minimize the dispersion between the red and blue lights.

Fig. 5. (a-e) Focal spots when the diffractive and fluidic lenses are combined to produce the best focus for the red and blue lights. The focal length values at the green wavelength are: (a) $f_{\text{diffractive}} = 1000$ mm, $f_{\text{fluidic}} = 252$ mm; (b) $f_{\text{diffractive}} = 500$ mm, $f_{\text{fluidic}} = 126$ mm; (c) $f_{\text{diffractive}} = 250$ mm, $f_{\text{fluidic}} = 63$ mm; (d) $f_{\text{diffractive}} = 400$ mm, $f_{\text{fluidic}} = 101$ mm; (e) $f_{\text{diffractive}} = 200$ mm, $f_{\text{fluidic}} = 51$ mm; (f) overall focal length of the hybrid system for the green, red and blue wavelengths.
wavelengths. The lenses showed acceptable optical properties and the test results were close to the theoretical predictions. This adjustable hybrid lens has no moving parts and would be useful for compact color imaging applications, and medical and ophthalmic imaging devices.

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