Hello, my name is Beatriz Demétrio and today I'm going to talk about the article: "two-photon direct laser writing of ultracompact multi-lens objectives"

1. INTRODUCTION

A. Motivation and Goal

The objective of this work is the manufacture of micro-lenses. Why is this fabrication and its use important? Micro-optics technology is becoming increasingly important in the development of optical systems. For example, recent improvements to CMOS image sensors would allow for further miniaturization of them, but there are no lenses to go along with it. Hence, it is even necessary to manufacture these lenses differently, which allows them to be in the order of micro.

These devices are currently in great use since they are a wide application, not only in image sensors, but also in various systems, such as:

- Photodetectors
- New illumination systems
- Bio-medical applications
- And so much more

With this article, it was possible to create micro lenses with good performance and fast manufacturing, but this will be explored later. But I will already leave an example of the applications of the devices obtained from the experience of this work: in endoscopies, as we see in the image, they will allow a non-invasive examination of the patient and thus obtain images of the interior of an organ or of another cavity within the same body. Another example, as I said, will be its application in CMOS image sensors, as we see in figure 2.

B. Other fabrications methods

On this slide, what we have are other manufacturing methods that already exist. Bear in mind that these are just a few examples and have nothing to do with my article, they were just placed to understand that effectively the authors' objective was to create a manufacturing method that did not have the same problems that these present.

So far, multi-lens optics, which have what we can consider good performances, but have several problems such as:

- There is a limitation of size, structure and dimensions associated with these methods;
- Inability to combine multiple elements
- Restrictions in designing the surfaces
- Problems with the alignment
- As well as the complexity and investment required to make them

These are schematics of two manufacturing methods given on the previous slide.

2. Designs, Fabrication and Methods used

The optical devices of this article consist of several different free-form lens elements with air in between. It takes only a few hours from lens design through production and testing to the final working optical device. We will see their design and their fabrication now.

C. OPTICAL DESIGN SOFTWARE: ZEMAX

In fact, contrary to what is written in the article, Zemax is not the software, but the company that created it. But this software is normally used for the design and analysis of both imaging and illumination systems. It works by modeling the propagation of rays through an optical system. The submicrometric compound lenses presented in this article are designed and optimized within this software.

These are the features used and built into the software.

It is also important to say, and it is not written here, is that the even aspheric surface parameterization was used as the surface type of the refractive interfaces. This is important because aspheric surfaces are normally used to compensate for optical aberrations and improve the image quality for each surface, but we will talk about this later.

After the simulations were done, the designs were exported into a computer-aided design file format and then transformed into a stereolithographic file format, to be able to carry out the next part.

D. Femtosecond Laser Lithography system

And so, what was used to manufacture these multi-lens objectives? Well, the compound lenses were fabricated by 3D dip-in direct laser writing using a commercially available femtosecond laser lithography system (which is included in the system in figure 7).

The complete optical compound system is manufactured from one single material. They therefore used a photoresist that exhibits high optical quality.

The numerous compound lenses were exposed by two-photon absorption (or 2PP) in an ultraviolet sensitive photoresist at a wavelength of 780 nm.

The designed structures were written layer-by-layer with 100 nm between the individual layers. For this, ultraprecise piezo actuators would move the sample in the axial direction after fabricating each layer. In the lateral direction the laser beam is guided by galvanometric mirrors parallel to the substrate. After the writing process, the lenses were developed in 2 baths with the objective of removing the non-photopolymerized material.

The fabrication method allows for optical elements with 3D structures with resolution beyond the diffraction limit, unlike the other manufacturing methods shown previously, which only propose a maximum resolution of only a few micrometers.

1. Results, their Discussion and Conclusions

Figura 9:

The writers start by compare composite lenses with different numbers of surfaces starting from 1 to 5 refractive interfaces (that's why we have the terms single, double and triple lens systems, respectively). They were designed to have an 80º FOV. In both simulations and measurements, barrel distortion and other field-dependent aberrations disappear as the number of refractive surfaces increases. (Talk about point d).

(In case she asks more anxiously about this image)

• In a) note that: although in the singlet lens design the rays through the field are not well visualized in a single point, in the triplet lens design the incident rays from different angles converge in a single point in the image plane in the rightmost interface.

• In b) we confirm what we got in a) -> the simulation using this test plot shows that for singlet lenses there are more blurred edges in the image, which in itself means that it exhibits strong field-dependent aberrations. We see that with increasing refractive interfaces, this field dependent on optical aberrations can be compensated.

• c) is for demonstration only. To quantify manufacturing tolerances, the surface is also characterized by microscopic atomic force measurements. They just showed skewed results for the len doublet and was that the surface roughness is 13nm r.m.s, and it is easily workable as we use a photoresist that exhibits high proximity effects.

• It's the same as c) but now the test graph will be at 20mm. We see the same as in the simulations but here in the measurements there is the following phenomenon: The fall of natural illumination (due to the law of cos for relative illumination) and the effect of the optical vignetting system become more visible. (It has to do with the Fresnel reflections on the 5 interfaces, which turn out to be quite substantial.

Optical vignetting is caused by the physical dimensions of a multi-element lens. Rear elements are shaded by elements in front of them, which reduces the lens' effective aperture for off-axis incident light. The result is a gradual decrease in light intensity towards the periphery of the image.

Figura 10:

Considering the results of figure 9, the authors only took the doublet and triplet systems, to better investigate their differences.

It was seen that in the triplet lens system in a) that in the first test chart the maximum resolution value was obtained (as obtained in the simulations) but when we moved to the other test chart, it displayed a yellowish hue, which was caused by the remaining photo initiator in the lens material. But when this lens is applied for example on the CMOS image sensor, this can easily be eliminated.

In b) we have the performance measurement for a doublet lens system with 3 refractive surfaces. Unlike the triplet system, here the maximum resolution was not achieved, and this can be seen by the images appearing blurry, due to chromatic aberrations.

(I'm not going to talk about c) but if the teacher asks why I say that the authors also didn't use it to compare with other lenses they've manufactured but with another micro imprint techonology method, which produces wafer-light objective lenses. – to say that it would be interesting to see in more detail but that with the given presentation time it was not enough to see this part carefully). – do not even appear in the supplementary

MTF or modulation transfer function basically serves to quantify the lens performance, more properly quantifying the loss of both contrast and resolution. It is measured on two graphs because due to lens aberrations, we know that some lenses are very good in resolving details pointed in one direction but not so good in resolving details pointed in another direction. Here we are only measuring the resolution.

This 10% modulation is since during manufacture there may have been a possible non-uniform shrinkage of the photoresist and therefore the final shape of the optical system is not perfectly as designed. However, despite this, they attribute this as the cause of obtaining better results in the Sagittal MTF than in the Meridional MTF.

Figura 11:

Then they decided to put bandpass filters, varying their distance to the clear lens, used for target illumination. In part a) of this figure, it was seen that effectively the 3 lenses had the same chromatic aberration behavior. While doing this, they had to adjust the focal position at each wavelength to obtain greater contrast and to reduce the effects of dispersion on the lenses at each wavelength, the target was imaged onto a different focal plane. And the result of this can be seen in part b), which are for the same triplet Lens of figure 2 and agree with what was seen previously, where you can see a high contrast for an FOV equal to 50°.

FOV – or field of view is the maximum area of a sample that a lens can image.

Figura 12 e 13:

So far, we have seen the behavior of lenses manufactured on a 170um thick glass substrate. But now we will move on to the results in which these lenses were manufactured directly in image sensors and in Imaging fibers, which is what figures 12 and 13 show.

In figure 12 we see several arrays of doublet lens systems with four refractive interfaces directly fabricated on an Omnivision 5647 CMOS image sensor. Each individual lens shows uniformly high quality and performs very similarly to neighboring lenses, and we see that quality in c) were the images acquisitions confirm the optical quality (because the numbers and the lines of the elements of group can be clearly distinguished).

In figure 13, we have an endoscopic application where a fiber, which has dimensions in the order of micro, was manufactured a triplet lens, just like the ones I've already shown. In b) we see the set-up used to make the measurements for this new system. And in c) it is verified that effectively the numbers of this test chart are clearly recognizable.

(If she asks:)

- How the lens was mounted on the fiber: for the writing process the triplet lens is centered by illuminating the opposite end facet and aligning it with respect to the writing beam.

- The fiber test chart was placed at 3mm to give the resembling typical endoscopic situations in medical imaging.

- Before making the lens on top of the CMOS image sensor, they removed the micro lens layer using a wooden spatula.

Conclusão:

It demonstrated the femtosecond direct laser writing of various ultracompact compound lens systems with numerous refractive surfaces. This method gives submicrometric accuracy and extremely good reproducibility, allowing for fast and reliable transfer from design and simulations to high-performance printed optics. Combining different optical materials for 3D printing may compensate chromatic and spherical aberrations in an achromatic lens design. Alternatively, the achromatic correction can be achieved by the combination of refractive and diffractive surfaces. Therefore, what was shown in this work was basically the interface between micro and nano optics and with was represented the paradigm Shift for micro-optics.