Consumer Electronic Optics: How Small a Lens Can Be Using Metasurfaces

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ABSTRACT

Miniature optics are used in many applications and particularly in consumer optics for such products as webcams, mobile phones, automotive components, endoscopes, tablets, and many other connected devices. Mobile phone cameras are probably the ones that have driven the race for shorter TTL over the past 10 years. Ten years ago, cell phone cameras were composed of 3-4 optical plastic elements within one camera lens; today it takes more than 6 optical elements to obtain mega pixel resolution. But it is still not enough. The market has an insatiable appetite for greater optical performance. Consequently, the lens system has become more complex and now may require more optical elements with more complex optical functions. In this context, can the metasurface lens play a role? In this paper, we will try to address this question and discuss how metasurfaces promise to become a game changer in the consumer electronics market.

Keywords: Lens Design, Metasurface, Dielectric, Nanofin, Aberration, Cell Phone, Camera Phone.

1. INTRODUCTION

Small lenses and small camera modules are now integral to our daily lives. We find them in our mobile phones, tablets, laptops, wearable devices, home entertainment systems, surveillance cameras, and the list goes on. A decade ago the main challenge in designing these lenses was to keep the TTL (total track length) roughly below 3.5 mm. So the question was: how can I place 3, 4, 5 or even 6 plastic lenses within such a small TTL. Figure 1 shows a state-of-the-art panoramic lens for cell phones produced back in 2014.

Figure 1. 5 year-old state of the art panoramic lens for the consumer market [1].

Today, things are different. Most all lenses protrude from the phone package, as shown in Figure 2. So the problem is the same but it has to do less about limiting the phone's thickness, and more about limiting the part of the lens which is outside the phone.

Figure 2. Both Samsung and Apple have used extra space outside the phone to fit the lens.

Another key factor now is the number of pixels which gets higher and higher as pixel size gets smaller and smaller. In 10 years, pixels have been reduced from 1.75 µm to 0.7 µm while their numbers have increased from 2 MPs to 64 MPs (soon to be released). Consequently, the focal plane array becomes very large.

Table 1 shows the diagonal dimension and the focal length of a 60 deg lens for each sensor (FOV = +/-30 deg). As you can see, the focal length, which is mostly the TTL of the lens (as it is difficult to design an efficient inverse telephoto in a cell phone due to the MTF requirement and the limited dimension), is increasing. For a 30 deg FOV lens, the EFL is 85% of the diagonal. For the new sensor, the EFL is significantly larger than the sensor family under 16 MPs. It seems clear that with the new generation of sensors with a format larger than 50 MPs, the lens TTL will become a problem.

Table 1. EFL estimation for various sensor formats (MPs and pixel pitch), indicative only.

Sensor (format)	Diagonal (mm, approximative)	EFL (60 deg lens, mm)
12 MPs (1.1um)	3.6	3.2
16 MPs (1.1um)	4.0	3.5
32 MPs (0.7um)	6.0	5.2
64 MPs (0.7um)	9.0	7.8

Table 2 shows that, to limit the focal length, a simple solution is to increase the field of view. As concluded in a previous paper 4 years ago [1], it seems that the solution will be to include a wide angle lens to fully exploit these large format sensors. In Table 2, the calculation is done using f-tan (theta) lens projection but for a wide angle lens, it is even more convenient to calculate the f-theta projection. It will come with significant distortion, and computational unwarping will be required. On this, I would like to say that even within distortion f-tan (theta) projection, for such wide angle higher than 80deg, the image becomes unpleasant and requires some dewarping to be more interesting for the user.

Table 2. Effect of the FOV on the EFL (for a 64 MPs sensor @ 0.7 µm pixel pitch)

FFOV (diagonal in degrees)	EFL (mm)
80	5.4
120	2.6
140	1.6
160	0.8 (or 3.2 f-theta)

The aim of this paper is to answer the following questions: how small can a lens become when using a metasurface? Given the context described above, what could be the role of a metalens in your cell phone? Can it help to reduce the number of lenses and/or the TTL? Can the metalens add new functionalities?

2. METASURFACE IN CONSUMER OPTICS

2.1 What is a Metasurface?

Over the years, many lens types have been used to deviate light. Refractive lenses are the best known and have been widely used on the market, so far proving to be the most efficient. Thirty years ago, diffractive lenses (diffraction rather than refraction) were heavily studied in order to figure out if they could be used to limit the weight of a lens since they can be planar on a very thin plate. However, this failed mainly due to the limited diffractive efficiency (or limited bandwidth) and unwanted stray light. The metasurface is a new lens type which does not use refraction and diffraction, both rather subwavelength light properties. To some extent, a metasurface is a diffractive lens where the 3D structures on the lens surface become smaller than the wavelength. In such regime, the diffraction is no longer valid and the light behavior becomes more and more complex. A recent paper from BANERJI et al [2] presents a very good comparison and discussion about flat optics using metasurfaces.

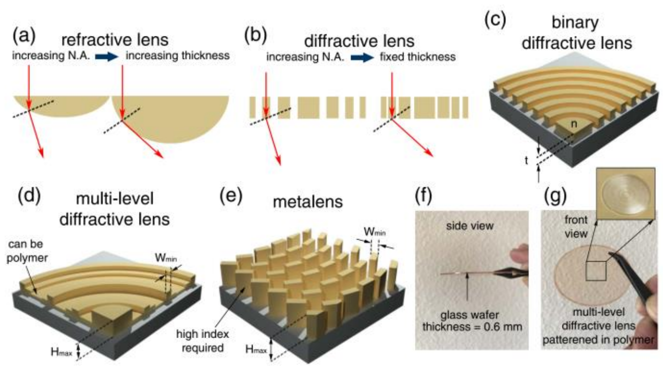

Fig. 1. Bending of light via (a) refraction and (b) diffraction. Schematic of the constituent element of a (c) conventional binary diffractive lens or grating, (d) multilevel diffractive lens (MDL), and (e) metalens. Photographs of a broadband visible MDL fabricated in a polymer film on a glass substrate are shown in (f) side view emphasizing the small thickness, which is dominated by the substrate and (g) front view.

Figure 3: Bending the light with various lens types (from 2)

2.2 Metasurfaces in lens design

The metasurface is not easy to describe mathematically even if we can describe how it works. From a fundamental standpoint, the problem of designing a lens is related to matching the lens-field to the focal-field under a certain illumination. As the metasurface cannot be described easily by an analytical function, the process must be done using a computational method (FDTD, modal…). This process is actually not compatible with a lens design approach where you want to balance the aberration over the entire element within your lens. This is a serious issue from a lens design point of view. At the moment, no lens design software incorporates any function to simulate a metasurface. Of course for on-axis applications, you can use a phase function (like a diffractive lens) but if you include some FOV, the approximation is no longer valid because the metasurface didn't behave as a diffractive lens at oblique incidence.

To include a metasurface in lens design, we must find a way to get a good analytical approximation in order to optimize it using a lens design process. So the metasurface can be defined as a DLL (Zemax) in order to be transparent to the lens designer.

A first simplified model has been identified at the moment which is a dielectric metasurface based on a nanofin, as shown in Figure 4.

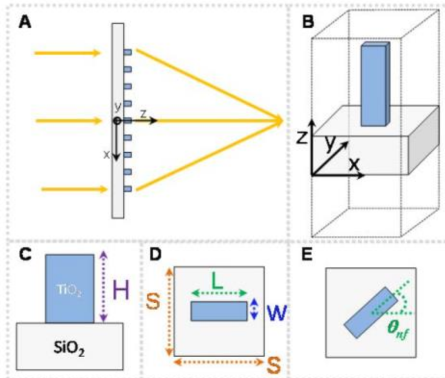

Figure 4 : Nanofin metasurface. The rotation angle of the structure is responsible for the phase shift produced by each nanopost.

Mathematically, for this type of metasurface, we can use an effective index approach from a waveguide approach [3, 4]. In that case, the electric field can be defined by the following equation:

$$\vec{E}_{out} = \begin{pmatrix} \left[\tau^{||}_{\chi\chi}\left(\tilde{E}_{X0}\cos(\theta_i) - \tilde{E}_{Z0}\sin(\theta_i)\right)\cos(\theta_n) - \tau^{\perp}_{\chi\chi}\left(\tilde{E}_{Y0}\sin(\theta_n)\right)\right]\cos(\theta_n)\, e^{i\beta_\chi \mathrm{H}} + \\ \left[\tau^{||}_{\nu\nu}\left(\tilde{E}_{X0}\cos(\theta_i) + \tilde{E}_{Z0}\sin(\theta_i)\right)\sin(\theta_n) + \tau^{\perp}_{\nu\nu}\left(\tilde{E}_{Y0}\cos(\theta_n)\right)\right]\sin(\theta_n)\, e^{i\beta_\nu \mathrm{H}} \\ \sim\sim\sim\sim\sim \\ \left[\tau^{||}_{\chi\chi}\left(\tilde{E}_{Z0}\sin(\theta_i) - \tilde{E}_{X0}\cos(\theta_i)\right)\cos(\theta_n) + \tau^{\perp}_{\chi\chi}\left(\tilde{E}_{Y0}\sin(\theta_n)\right)\right]\sin(\theta_n)\, e^{i\beta_\chi \mathrm{H}} + \\ \left[\tau^{||}_{\nu\nu}\left(\tilde{E}_{X0}\cos(\theta_i) + \tilde{E}_{Z0}\sin(\theta_i)\right)\sin(\theta_n) + \tau^{\perp}_{\nu\nu}\left(\tilde{E}_{Y0}\cos(\theta_n)\right)\right]\cos(\theta_n)\, e^{i\beta_\nu \mathrm{H}} \\ \sim\sim\sim\sim\sim \\ \tau^{||}_{\zeta\zeta}\left(\tilde{E}_{Z0}\cos(\theta_i) - \tilde{E}_{X0}\sin(\theta_i)\right)e^{i\beta_\zeta \mathrm{H}} \end{pmatrix},$$

where the output field depends on the substrate index of refraction, nanofin dimension, orientation (theta$_n$), incident angle (theta$_i$), and polarization of the incident light. The equation is not easy to compute but it is an analytical model. We are still working on the model to see how the equation can be simplified for specific consideration in polarisation or small angle of incidence. Using a simplified or the entire equation, we have defined a process in Zemax that can be used to take advantage of all optimisation features in the lens design software. As stated earlier, we will write a DLL that will allow us to use a Zemax optimization algorithm that is speed efficient and simple to use. The main drawback is that we will have to implement the equation in C++ but once done, the DLL can be transferred easily to everyone.

Creating a user defined surface in Zemax allows to easily leverage Zemax's built-in optimization algorithm while retaining flexibility. Arbitrary parameters can be defined to represent the higher level variables which directly represent the physical properties of the surface. How these variables impact the ray tracing can then be implemented. Dependencies on the ray position at the surface, angle of incidence and other factors can be implemented to create a unique behavior. Below, as a simple example, a DLL surface was created to alter how the refractive index of the material is perceived by the incident rays. This variation is related to the x,y coordinates and the angle of incidence. However, the exact behavior is controlled via higher level variables here named RodLength, RodWidth and RodHeight. These higher level variables can then be optimized using a standard approach in Zemax.

	Surface Type		Radius	Thickness	Material	Semi-Diameter	Conic	RodLength	RodWidth	RodHeight
0	OBJECT	Standard	Infinity	Infinity		Infinity	0.000			
1		Standard	Infinity	2.500		3.098	0.000			
2	STOP (aper)	User Defined	Infinity	1.000	BK7	1.000 U	0.000	7.105 V	-0.274 V	7.208 V
3		Standard	Infinity	5.000		1.172	0.000			
4	IMAGE	Standard	Infinity	-		2.511	0.000			

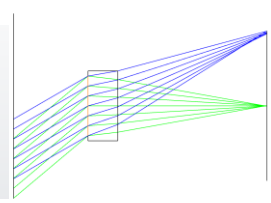

Figure 5 : DLL in Zemax where variables can be inputted by optimisation.

2.3 Metasurface in consumer optics

The first idea can be to refer to a cell phone lens. The following figure shows two typical cell phone lenses. As we can see, not much space is available to add new components. Moreover, the TTL is already about 7 mm for both lenses.

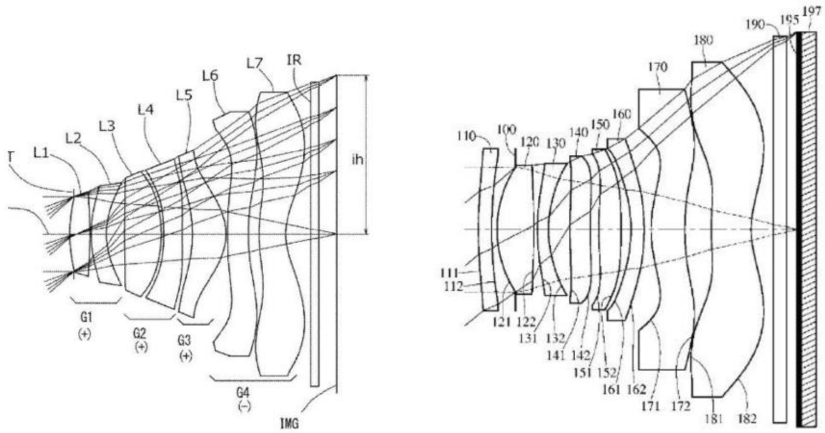

Figure 6 : Left : 7 elements, f = 6.76, F/2.4, HFOV = 41.2 (US20140376105A1), right: 8 elements, f = 5.38, F/1.90, HFOV = 39.0 (US9523841B1).

The thicker elements on both designs are the plano positive elements as well as the W-shape lenses (last two elements). These W-shape lenses are required to compensate for the extreme field curvature and astigmatism. These lenses are also used for a more hidden reason. In fact, in the cell phone the sensors exercise a very severe constraint on the chief ray angle incident on each pixel. This is due to the fabrication of the sensor that minimises the light loss, as shown in Figure 7. However, the main drawback of those lenses is the change in the f-number which leads to a low relative illumination.

So naturally, we can think that a metasurface can be used to limit the thickness of the plano-positive element, to replace one or two W-shape lenses, or to solve the relative illumination problem and to match the chief ray angle (CRA).

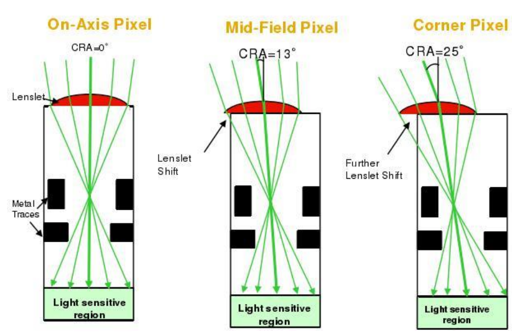

Figure 7: CRA variation according to the position on the sensor.

3. THE PROBLEM & THE SOLUTION

Using a metalens as a standard lens may not be a good idea. The main issue is efficiency because the lens is very sensitive today to the light polarization state. A mixed pattern metalens is now under development to mitigate this but we are not there yet. To some extent, the metalens suffers from the same problem as the diffractive lens, which is not used for broadband applications due to its poor efficiency and stray light problems. In the literature, as discussed in ref 2 (supplement), we can find a list of almost all the metalenses fabricated so far with their efficiencies: the efficiency range from 2% to 90% for very narrow band applications. But none of them describe where the unwanted light goes within the optical system. Consequently, the metalens is clearly not ready yet for imaging applications.

So what's next! This is it!

It is not over yet. The situation will evolve over the next few years and the work described in section 2.2 will pay-off and maybe open a new area. For the moment, we can study metalens behavior in order to find a concrete application. From a lens design point of view, the metalens presents these main characteristics. Firstly, the dispersion can be easily tuned to unprecedented levels. Secondly, it is polarization sensitive. What we have to do is to think about applications that can use one or both of these functions.

A niche application could be the TOF module where VCSELL illumination can be redirected to the scene using a flat optical surface with a metasurface. The detection module can also use a flat metasurface with polarization control to find information about texture for example through the use of degrees of polarization (DOP).

A second application can be a multispectral miniature system on your cell phone that can be used to diagnose skin issues, help apply makeup uniformly…

4. CONCLUSION

It is premature to consider using metalens/metasurface in consumer electronic optics. We can see that a flat metalens can be used as a phase lens. The gain in TTL is not clear for now. The complexity of the design which involves the electromagnetic field somehow represents a very high constraint. The efficiency is yet to be proven.

However, this may change within a timeframe of 1-2 years using new developments in modeling that can port the metasurface within the lens designer world.

Hopefully, we can come up with innovative applications right now that will involve some particular feature of a metasurface to propel your cell phone's optical system to the next level.

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