REVIEW AND DESIGN A MOBILE PHONE CAMERA LENS FOR 21.4 MEGA-PIXELS IMAGE SENSOR

by

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STATEMENT BY AUTHOR

The master's report titled "*Review and Design a Mobile Phone Camera Lens with 21.4 Mega-Pixels"* prepared by Ying Ting Liu has been submitted in partial fulfillment of requirements for a master's degree at the University of Arizona.

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1. Introduction:

In November 2000, Sharp unveiled the first mobile phone with camera to the market, J-SH04 with standard resolution 0.3 Mega-pixels (MP). Then, Sony Ericsson stepped things up over the Sharp's original design. They produced a new camera mobile phone with 2MP camera, and added a bright dual-LED flash. This was a big revolutionary improvement of the design of camera mobile phone. In the last decade, the pixels on camera of mobile phone has increased from 2MP, 5MP, 8MP, to 12MP and 21.4MP, even 41MP (Nokia Lumia 1020).

The camera mobile phones are gradually substituted for the conventional digital camera due to its portability, convenience to share with family, friends instantly. At the same time, the development of compact camera modules is the result of the development of Metal-Oxide-Semiconductor (CMOS). Before the image sensor CMOS has not developed, it was very difficult to integrate the high pixel camera lens in mobile phone, and the length of the lens was usually greater than 1cm.

Now, the development of CMOS has been grown up, the amounts of pixels on image sensor could be significantly increased, and the size of pixel has decreased, from previous size 8 μm to 1.12 μm, even 1.0 μm (See Fig. 1). While the pixel size scaling down, the amounts of pixels on an image sensor greatly increasing. Therefore, the image sensor can provide the higher image resolution. With the continuous upgrade metrology for producing compact camera lens, the requirement of high imaging quality of people raises. Therefore, the design, production of high quality, low cost imaging and more compact camera module has become a popular field.

According to the above development form, the report is based on the selection of reasonable initial lens structure, and design a telephoto lens for compact camera module with 21.4 MP pixel image sensor, OV21840, produced by OmniVision.

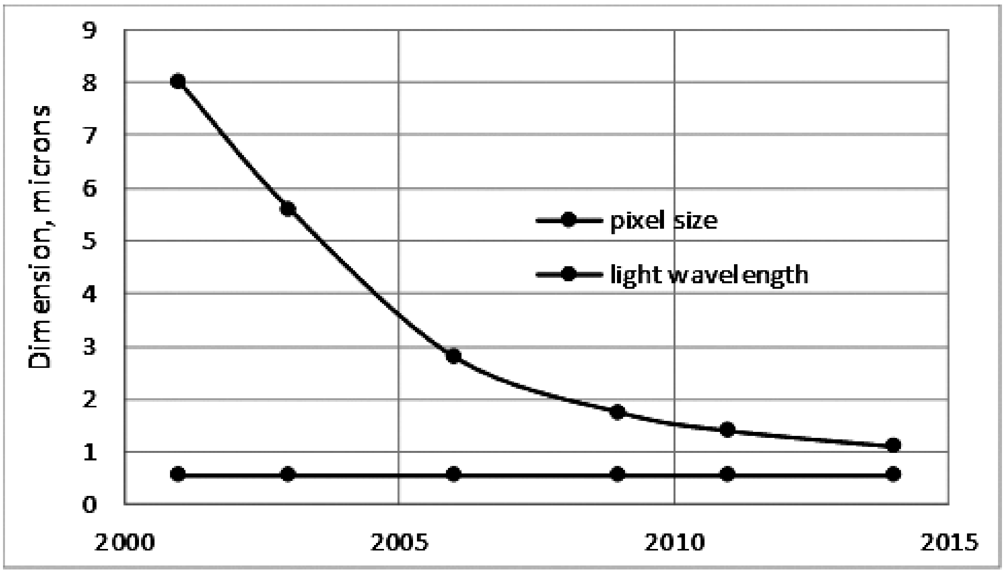

Fig 1. Development of pixel size

2. History of camera mobile phone

2.1 The first camera mobile phone in the world

The camera mobile phone is a mobile phone with a front/rear compact camera which is able to capture photographs instantly and record video. The first mobile phone with a built-in camera was manufactured by Sharp and released in Japan by J-Phone in November of 2000, named J-SH04. The J-SH04 could take the photos with 0.11 MP resolution.

Fig 2. Photo taken by J-SH04

Fig 3. J-SH04

However, there was a strongly argument that the first mobile phone with a built-in camera was produced by Samsung and released in Korea in June of 2000, named SCH-V200. It could capture the photo at 0.35 MP resolution. The major difference between them was the fact that J-SH04 allowed people to send their photos electronically. But, the Samsung SCH-V200 camera mobile phone just shared the same case and battery, it does not integrate with the phone function. The image of the SCH-V200 had to be transferred to a computer, then send to others by email. It was only a half-integrated mobile.

Fig 4. Samsung SCH-V200

Later, released in early 2002, the Nokia 7650 was definitely one of the most important phones ever. It rose up over Sharp's original camera phone with a 0.3 MP camera, 2.1-inch display, faster processor (104MHz) and 4 Mega-Bytes of internal storage. Then, in 2005, there was a greatly improvement of resolution of camera in mobile phone. The Song Ericsson K750i was unveiled to the market with 2 MP. It featured of the bright dual-LED flash that could improve the image quality when photographing. This is the new generation of camera mobile phone.

Fig 5. Nokia 7650

Fig 6. Song Ericsson K750i

Moreover, not only the number of pixels of camera increasing, it also added more specifications to improve the image quality. The Sony Ericsson K800i had a 3.2 MP camera with auto-focus, image stabilization, and Xenon flash.

Fig 7. Song Ericsson K800i

The first camera mobile phone with 5 MP was produced by Nokia. Nokia followed up its 2005 Nokia N90 (the first with a Carl Zeiss lens) and the 2006 Nokia N93 (with 3x optical zoom) with the technically gifted Nokia N95 in 2007. The N95 had much new features: 3.5 internet technology, GPS and multimedia capabilities. The camera also carried Carl Zeiss optics with LED flash. Also, the 330 Mega-Hz processor make it faster to take the pictures.

Fig 8. Nokia N95

Fig 9. LG viewty KU990

At the same time, there was the other stand-out camera mobile phone hit the market in 2007, LG viewty KU990. It also rolled up with a 5 MP camera, a Xenon flash and 3 inches touchscreen. The most impressive thing is that it features a movable wheel on the back that allowed for up to 16x digital zoom.

2.2 High-pixels period (Over 10 MP)

Due to requirement of people in photographing daily with high image quality, the higher resolution of camera mobile phones came out since 2010. During this period, the image resolution of built-in camera mobile phone increased to 12 MP, 16 MP, 21 MP and even 41 MP. The camera mobile phones with 12 MP were produced by several companies, Sony Ericsson Satio and Samsung Pixon12 M8910 are most popular. Not only with 12 MP camera, they also had several specifications, such as smaller f-number, full touchscreen, smile detection, touch focus, object tracking auto focus and image stabilization.

As the resolution increasing, some companies also tried to do a novel way to improve image quality, not only utilizing image sensor with high resolution. HTC, for example, unveiled a novel smartphone HTC one. It claimed that packing in and combining pixels seems to a prime way of gaining a better image quality. They packed in a brand-new camera imaging technology, known as UltraPixels.

UltraPixels technology was developed by HTC, it could quickly decide that letting in as much as light as possible and created the better images, even imaging in the low light environment. The sensor has twice the surface area of the 8 MP solutions from competitors, and far larger than standard 13 MP sensors. A new dedicated imaging chip took the strain to help manipulate raw image data, it means that less data loss before editing and better images.

Fig 10. HTC One

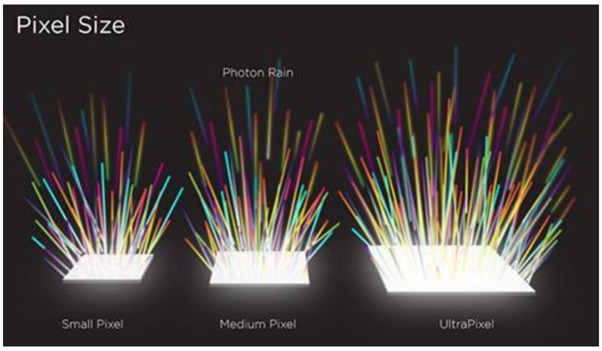

Fig 11. Pixel size comparison

Fig 12. Image comparison

2.3 Dual-camera period (2016-Present)

The concept of dual-camera was investigated and researched for many years since the special requirements of people in capturing photo with mobile phone, such as taking portraits and capturing landscapes. It was firstly introduced by HTC EVO 3D in 2011, featuring of 3D recording and 3D image. Since then, the mobile phone companies kept producing the dual-camera with high image quality in smartphone.

Introduced by HTC (HTC M8), perfected by Huawei (Huawei P9) and followed by Apple (iPhone 7 Plus). There are truly useful for three things: portrait photo (blur background), telephoto (optical zoom) and wide-angle photo. The specification of iPhone 7 Plus: 12 MP main camera with F/1.8 aperture, 12 MP 2x zoom secondary camera with F/2.8 aperture and optical image stabilization. For the near term, it seems that dual-dual-camera systems will take over the task of pushing mobile photography forward. They will keep updating with large aperture (collect more light in low light area), widely angle and high image quality.

As the advanced semi-conductor manufacturing technology has allowed the pixel size of sensors to be reduced and compact photographing systems have gradually evolved toward the field of higher mega-pixels, there is as increasing demand for compact photographing systems featuring with better image quality. The more distant future might hold a greater number of lenses and higher pixels sensors.

Fig 13. Dual-camera in smartphone

Fig 14. iPhone 7 Plus

3. Review of Historical Patented Designs

By reviewing the patented designs of cameras lens of mobile camera phone, the following specifications can be found:

1. The pixel size of image sensor varies from 1.0μm to 2.0μm. The pixel size of 1.12μm is common to use in high-pixel camera on the market.
2. Five to six elements are often used. The thickness of elements becomes thinner. Ultra-thin lens elements are used for manufacturing and provide high image quality.
3. The field of view (FOV) of the mobile camera is large. Common FOV values are 70° to 80°.
4. The f-number of mobile camera phone usually varies from 2 to 3. For getting high quality image at low light environment, the designer chases the lower f-number. It can be found the f-number of 1.8, 1.7, even 1.6 are used in the camera lens of mobile phone. The requirements of telephoto lens in dual-camera module, it is common to use f-number of 2.8 and 2.4.
5. The plastic optical materials are greatly used in lens elements. It is suitable to make the complex surfaces which is common to use for correcting aberrations in camera lens of mobile phone.

4. Design method

The designs of mobile phone camera lenses are very different than we are used to seeing for larger cameras. In recently, the lens designers face challenges when designing miniature camera lens compared to conventional large-scale camera lenses. They must consider different product requirements, such as shortest possible length, chief ray angle and relative illumination. The most restriction thing is the packing size because the thickness of mobile phones become thinner and thinner. The image sensor is also considered when designing the miniature camera lenses.

There are two types of image sensor, charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS). CCD sensors convert pixel measurement sequentially using circuitry surrounding the sensor. They contain an array of capacitor that gathers a charge that is proportional to the amount of light that is hitting it. Using a single amplifier for all the pixels to convert photons to electron charges. CCDs are manufactured in foundries with specialized equipment and this is reflected in their higher cost. There are some distinct advantages of a CCD sensor: less noise and higher quality images (especially in low light), having better depth of color (twice dynamic range than CMOS sensors), higher resolution and more sensitive to light.

On the other hand, CMOS sensors convert pixel measurements simultaneously, using circuitry on the sensor itself. CMOS sensors capture light intensity via an array of photo-detectors that are coupled with an amplifier to attain a high enough to charge to quantity. They use separate amplifiers for each pixel. CMOS sensors are commonly used in Digital single-lens reflex cameras (DSLRs) and mobile phone cameras since they are faster and cheaper. The advantages of CMOS sensors: faster at processing images (active pixels and analog to digital converter on the same chip), lower power consumption (100 times less than CCD), manufacturing processing is easier and less expensive. The table1 presents comparisons between CCD and CMOS.

Sensor type	CCD	CMOS
Structure	Sigle amplifier for all pixel	Photo-detectors with amplifier
Sensitivity to light	High	Low
Noise	Low	High
Processing image speed	Slow	Fast
Power consuming	High	Low
Cost	High	Low

Table1. Comparison of CCD and CMOS

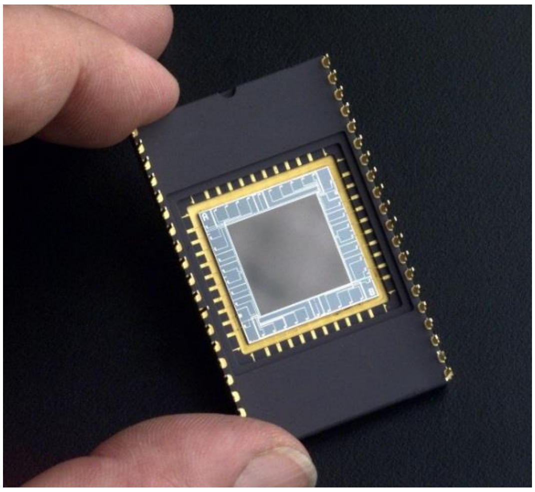

Fig 15. CCD (A specially developed CCD used for ultraviolet imaging in a wire-bonded package)

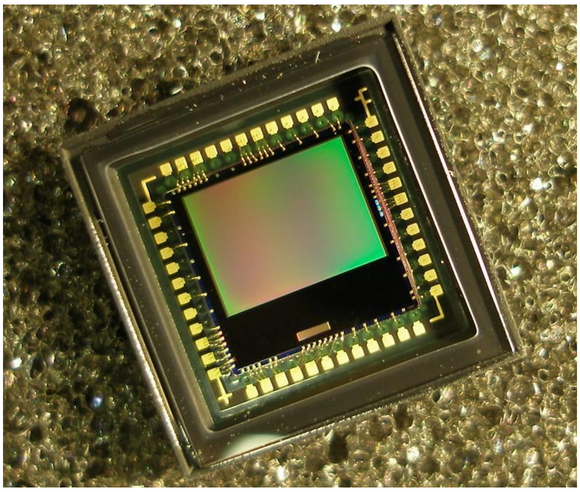

Fig 16. CMOS

Considering the cost and trend of requirement of photographing on mobile phone, the image sensor OV21840(CMOS) produced by OmniVision in 2015 is chosen to design in this report. It supports active array of 5344 x 4016 pixels (21.4 Mega-pixels) at 27 frames per second (FPS, Frame rate), records 4K video at 30fps in HDR mode, 1080p HD video at 90FSP, and 720HD video at 120FPS (slow motion). The pixel size is 1.12 micro-meter x 1.12 micro-meter. The Table2. Presents the specifications of image sensor OV21840. So, According to the parameters of the CMOS image sensor and the actual needs of the camera. The design parameters of the mobile phone camera lens are discussed below.

*FPS (Frame rate): the frequency (rate) at which consecutive images are displayed in the living display. The human vision system usually can process 1 to 5 images per second and perceive them individually, while higher rates are perceived as motion.

	Specifications
Sensor	OV21840
Active array	5344 x 4016 (21.4 Mega-pixels)
Pixel size	1.12 um x 1.12 um
Image area	6.321 mm x 4.47497 mm

Table2. Specifications of OV21840 (CMOS)

5. Typical Specifications for CMOS Sensor OV21840

5.1 Image height

From the image area of sensor, we can get the image height for designing. The diagonal of sensor is $\sqrt{6.321^2 + 4.47497^2} \approx 7.906\ mm$. The image height is half of diagonal of image sensor, $\frac{7.906\ mm}{2} \approx$ 3.953 mm. To prevent image vignetting, the image must be a little bigger than 3.953 mm. So, the image height is set for 3.96 mm.

5.2 F-number(F/#)

The f-number of an optical system is the ratio of focal length to the diameter of the entrance pupil, an important concept in optics. It's a quantitative measure of lens speed, also known as the focal ratio or f-stop. Here, for designing a telephoto lens in mobile phone, set the f-number to be 2.8 which is most commonly in the market.

5.3 Half field of view(HFOV)

The field of view (FOV) of an optical system is often expressed as the maximum angular size of the object as seen from the entrance pupil. The maximum image height is also used. Here, considering the common requirement of customers in photography, set the field of view for 78° , and half field of view is 36° ($\theta_{\frac{1}{2}}$).

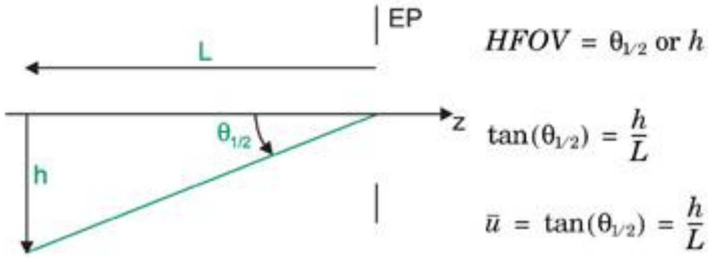

Fig 17. Half field of view

5.4 Effective focal length (EFFL)

From the Fig. 18, the relationship between image height (h), focal length and half field view (θ) is:

$$f = \mathrm{EFL} = \frac{h}{\tan\theta}$$

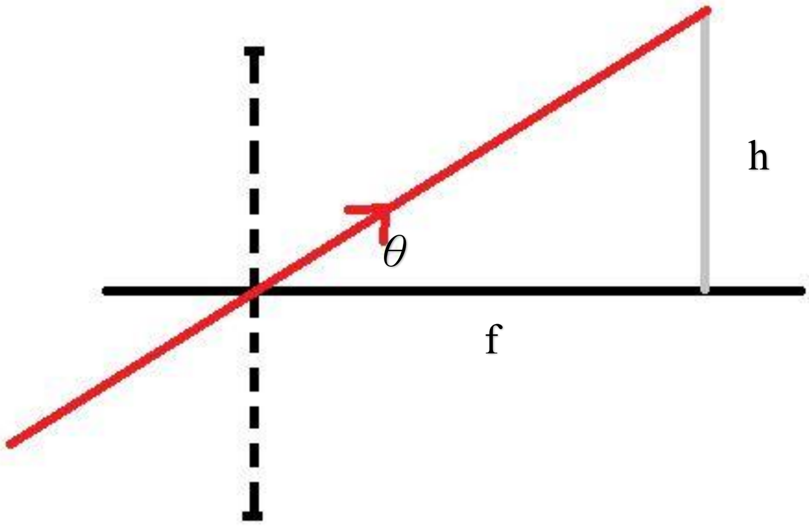

Fig 18. Relationship between image height and focal length

So, the focal length is $f = EFL = \frac{h}{\tan\theta} = \frac{3.95}{\tan 38} = 5.0685$ mm.

6. Goals of designing

6.1 Modulation Transfer Function (MTF)

The modulation of an optical system is a measurement of its ability to transfer contrast at a specific resolution from the object to image. It is a specification between resolution and contrast. As line spacing decreasing (the frequency increasing) on the test target, it becomes difficult for the optical system efficiently transfer this decreasing in contrast. As a result, MTF decreases. For designing a miniature camera, the MTF criteria is related to the Nyquist frequency of the sensor. From the pixel size of the sensor, 1.12 um, the maximum spatial resolution of the system is:

$$V_{Nyquist} = \frac{1}{2\ X\ CMOS\ pixel\ size} = 446.4\ \frac{lp}{mm}$$

So, the resolution of the system is 446.4 lp/mm. If the requirement of frequency meets Nyquist frequency, the MTF should be 0.1 by calculating, the Airy disk size of the configuration is:

$$D_{Airy} = 2.44\lambda \times {}^{F}/_{\#}$$

So, the $D_{Airy} = 4.08\ \mu m$, pixel size should be close to the Airy disk size.

6.2 Lateral Chromatic Aberration (Lateral Color)

The off-axis light bundles the corresponding central ray is referred to as the chief ray. The height of the chief ray at the image plane defines the image size. The refraction of chief ray varies with the wavelength. Different wavelength would be imaged at a slightly different height on the image plane. Here, the amount of lateral color is restricted as smaller than a pixel size of the image sensor. The color-offset would not appear on the image sensor. So, the lateral color is restricted as $1.12\ \mu m$.

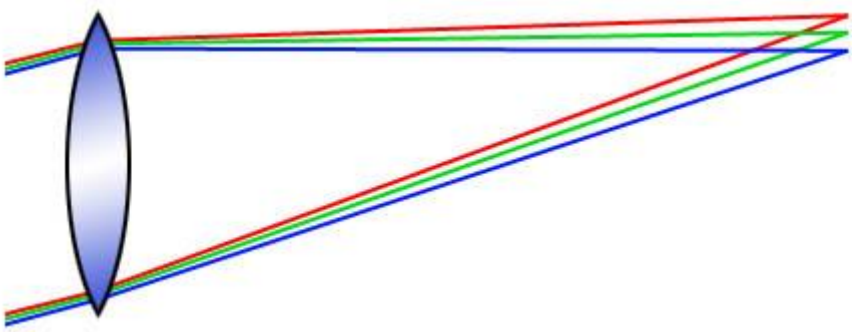

Fig 19. Lateral chromatic aberration (Lateral color)

6.3 Optical Distortion

Optical distortion occurs when image magnification varies with the image height.

$$\text{Optical distortion} = \frac{Real\ image\ height - Ideal\ image\ height}{Ideal\ image\ height} \times 100\%$$

As the field increasing, the distortion increasing as well. For designing a mobile phone camera lens, the optical distortion is restricted less than 1%.

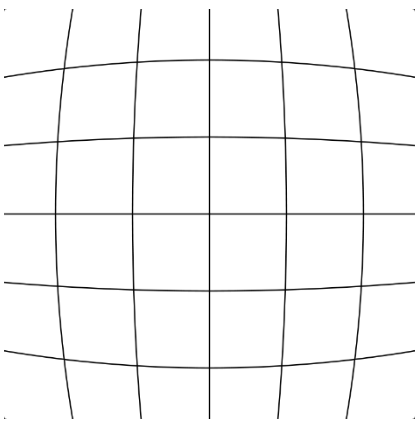

Fig 20. Barrel distortion

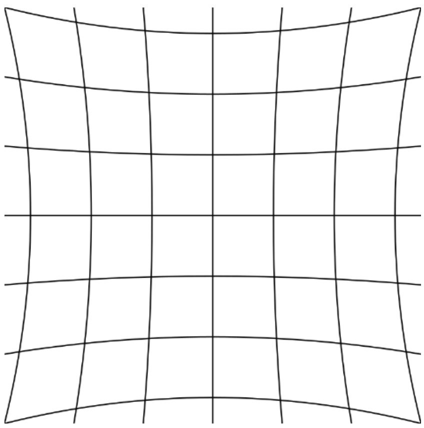

Fig 21. Pincushion distortion

Since the mobile phone camera lens is not symmetrical system, it is difficult to correct the distortion. In lenses with large distortion, the negative distortion combined with the blur, caused by other aberrations, can balance the cosine-fourth effect, producing more uniform relative illumination (RI).

6.4 Chief Ray Angle (CRA)

The chief ray angle of a mobile phone camera lens is related to the acceptance angle of the infared (IR) cut-off filter and micro lens array embedded at the surface of the sensor. The chief ray angle of a lens need to be within an allowable value, otherwise image blurring or vignetting occurs. According the specification of image sensor (OV21840), the chief ray angle should be limited less than 34° to avoid image blurring or vignetting. The CRA impacts the relative illumination (RI), which usually is set to 40 % at the corner. For better CRA control, the aperture stop is placed close to the front, away from the image plane. The position of aperture stop and strong aspheric next to image plane produce exit pupil spherical aberration, which reducing the CRA.

6.5 Relative Illumination (RI)

Relative illumination trends to decrease towards the peripheral fields because of the cosine-fourth law. It is related to the angle of incidence by cosine-fourth law. The illumination onto the image plane decreases proportionally with the angle of incidence of the chief ray to the image. As the angle increasing, the value of cosine-fourth decreasing, the relative illumination decreasing, and then resolution also decreasing.

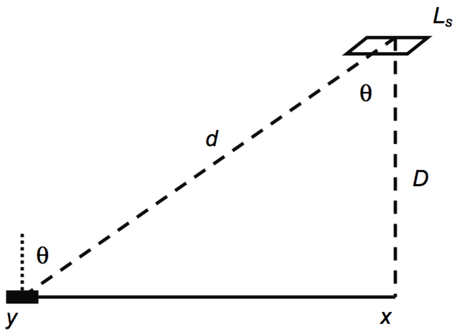

Fig 22. The cosine-fourth law

$$E = \frac{LA_p \cos\theta^4}{D^2}, RI \propto \cos\theta^4$$

For the designing of mobile phone camera lens, the largest angle is 38°, so the relative illumination should be 38% to avoid being dim at the corner of the image sensor.

$$RI \propto \cos\vartheta^4 = \cos 38^4 \simeq 0.38 = 38\%$$

Parameter	Value
Wavelength (μm)	486-656
Image height (mm)	3.96
Half field of view (HFOV)	38°
Focal length (mm)	5.06
Lateral color	< 1.12 μm (a pixel size)
Optical distortion	< 1%
Relative illumination (RI)	> 38%

Chief ray angle (CRA)	$< 34^{\circ}$
Total track (mm)	< 6.5

Table3. Design specifications for OV21840 (CMOS) image sensor

6.6 Telecentric System

A telecentric system has the unique property of maintaining a constant magnification over a specific range of object distances. When the aperture stop is located at the front focal plane, the exit pupil (XP) is at infinity, the system is image-space telecentric. Defocus of the image plane will not change the image height. When designing a mobile phone camera lens, the exit pupil (XP) of the imaging system is located far away from the image plane, thus light will be projected onto the image sensor at a nearly perpendicular angle, and produce more uniform illumination at the corner of imaging system. The telecentric feature is very important to the photosensitive power of current solid-state sensor as it can improve the photosensitivity of the sensor to reduce probability of the occurrence of shading.

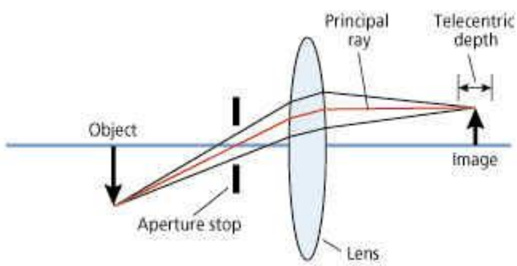

Fig 23. Image-space telecentric system

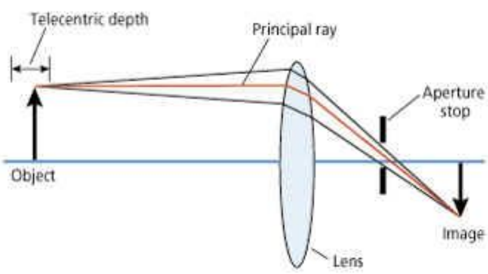

Fig 24. Object-space telecentric system

6.7 Material

In recently, the plastic lens becomes the main stream for manufacturing miniature mobile lens due to its advantages. The main reason is cost. It is much cheaper for mobile phone camera manufacturing to use plastic rather than full-glass lenses. For example, the glass lenses usually cost $20-$40, but the plastic lenses only cost under $5. Also, the plastic can be a little more durable, given the tiny and fragile nature of glass. Using plastic optical elements is good for reduction of weight due to relatively small density. It is also good for manufacturing the complicated optical elements, such as aspherical lens which often constructs the elements of system.

6.7.1 Structural Stability

However, there are some disadvantages for using plastic lens. Theses lenses will tend to distort the picture, especially when there is a little bit movement or the higher resonant frequency of a certain component. The further resonant frequency is from the excitation frequency, the smaller is the oscillation amplitude. The angular resonant frequency ω of a component is presented by stiffness k and its mass m:

$$\mathrm{k} = \frac{EI}{l^3} = \frac{E}{l^3} \cdot \frac{bh^3}{12}; m = \rho bhl$$

$$\omega = \sqrt{\frac{k}{m}} = \frac{h}{2\sqrt{3h^3}} \cdot \sqrt{\frac{E}{\rho}}$$

where E is Young's modulus, l is the length, b is the width, h is the height of the beam and I is the geometrical moment of inertia. From the assumption show above, the resonant frequency is proportional to square of the ratio E/ρ. To have great structural stability, the ratio should be as large as possible. The other representing ratio are (as small as possible):

For choosing material to design, we must select plastic for the minimize deflection.

Deflection at constant mass	$\frac{\rho^3}{E}$
Deflection at constant thickness	$\frac{\rho}{E}$
Mass at constant deflection of a certain component	$\sqrt{\frac{\rho^3}{E}}$

Table4. Deflection for structural stability

6.7.2 Thermal Stability

Assuming a constant heat flux φ (W/m^2) from environment flows through the material, the change in temperature is given:

$$\Delta\mathrm{T} = \frac{\varphi}{\lambda}$$

where λ is the thermal conductivity. In the steady state, the linear thermal distortion is determined:

$$\frac{\Delta L}{L_0} = \alpha \cdot \Delta\mathrm{T} = \varphi \cdot \frac{\alpha}{\lambda} \;; \frac{\Delta A}{A_0} = 2\alpha \cdot \Delta\mathrm{T} = 2\varphi \cdot \frac{\alpha}{\lambda} \;; \frac{\Delta V}{V} = 3\alpha \cdot \Delta\mathrm{T} = 3\varphi \cdot \frac{\alpha}{\lambda}$$

The assumption shows in constant heat flux into the component the distortion due to thermal expansion is proportional to the ratio α/λ. To have good thermal stability, the ratio should be as small as possible. For the case of transient thermal changes heat storage, the amount of heat Q required to increase the temperature of a unit of a sub stance by one degree is given by:

$$\mathrm{Q} = C_p \cdot m\Delta T$$

where C_p is the heat capacity, and m is mass of the unit. The diffusivity D is determined by:

$$\mathrm{D} = \frac{\lambda}{\rho C_p}$$

For a given amount of heat, to keep the temperature change of a certain optical element low, the heat capacity should be as high as possible. To have homogeneous distribution on a component, large diffusivities D are desirable. However, the heat capacities of plastic optical materials are extremely low. The plastic component is very sensitive with the heat incident. A large amount of thermal gradient will occur on a component due to small diffusivity. Thus, the deflection would be large in plastic optical material elements. The ratio α/D is proportional to this kind of transient distortion and is expected as small as possible.

6.7.3 Moisture Absorption

Another instability issue of plastic optical element is the change of volume in high-humidity environment, called moisture absorption. The moisture absorption is not only influences on dimensions and densities, but also changing the refractive index of plastic optical materials. Cyclooefin Copolymer (COC) is known as low moisture absorption, PMMA has large moisture absorption need to be careful in designing optical system.

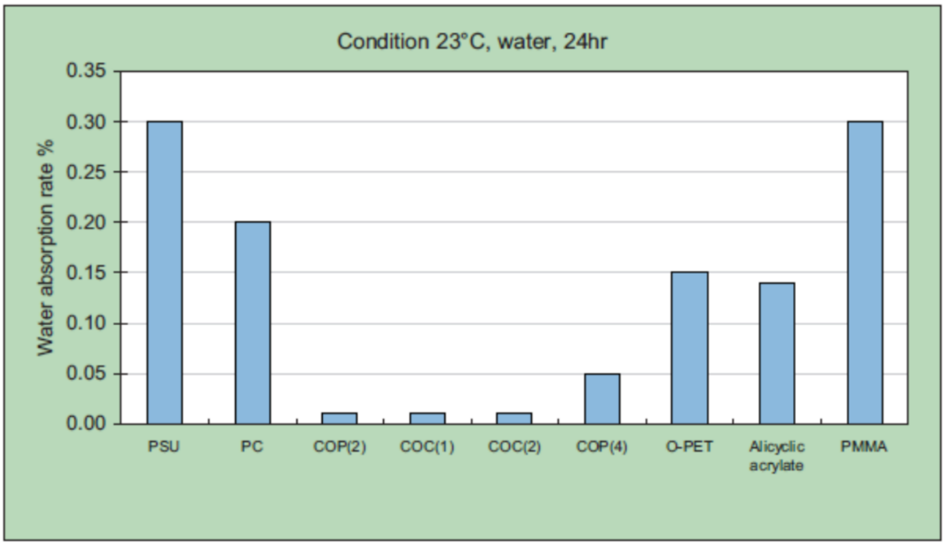

Fig 25. Comparison of the water absorption of some optical polymers

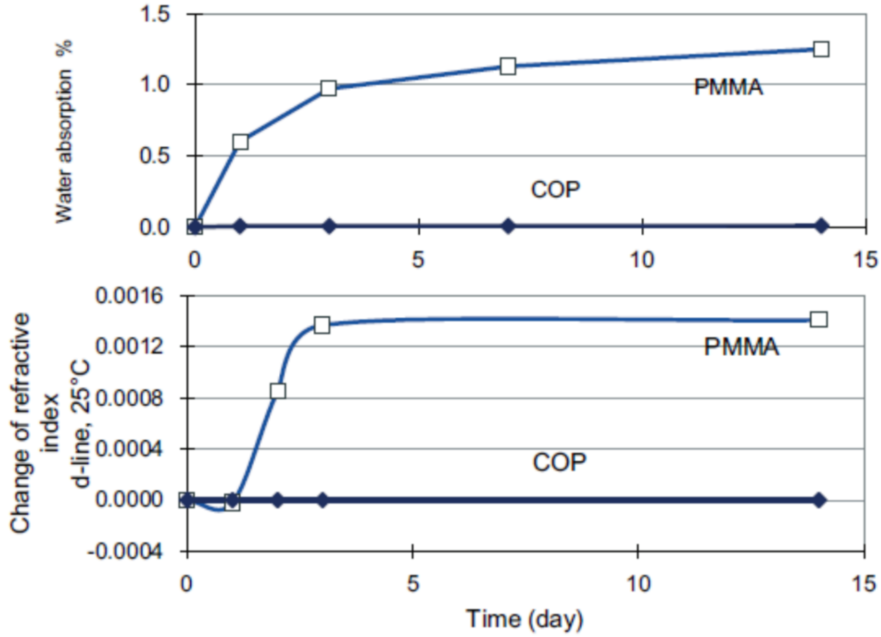

Fig 26. Change of refractive index due to water absorption for PMMA

	Glass	Plastic
Cost	More	Less
Weight	Heavy	Light
Structural Stability	High	Low
Thermal Stability	Good	Bad
Moisture Absorption	Good	Bad
Scratching	Good	Bad

Table5. Comparison between glass and plastic

7. Design and Optimize Process

7.1 Selection of Initial Structure

For designing a mobile camera phone lens, an optimum design usually starts from the choice of initial structure. A better initial structure can decrease the optimization steps and time. There are two ways to find the initial structure: one starts from the paraxial approximation, setting initial structure then adjusting the specifications until meet the requirement of the design. This method requires solid theoretical foundation and wealthy empirical design experience. In contrast to paraxial method, the best and fast way is to select one suitable initial configuration directly from the patent, then optimize it for the requirements.

In this report, the CMOS image sensor OV21840 with a pixel size of 1.12μm is chosen for designing. The initial structure of the design is chosen from the patent U.S. 9,488,803, which has six plastic lenses with high image quality. Changing and adjusting the field, materials, and focal length of original structure to meet the requirements, which are calculated from the specifications parameter in Table3. The plastic optical material for the lenses are Cyclooefin Copolymer (COC) and OKP4. The refractive index and Abbe's number are 1.53, 56.2; 1.61, 26.9. These two types of optical plastics have great heat resistance, mechanical, physical, and optical properties, their densities are very small. They are suitable to produce the aspheric lens which can be effectively correct aberrations. The general formula of aspheric lens is shown as below:

$$\mathrm{sag(r)} = \frac{Cr^2}{1+\sqrt{1-(K+1)C^2r^2}} + A_1r^2 + A_2r^4 + A_3r^6 + A_4r^8 + \cdots\cdots$$

where C is the curvature of the aspheric vertex, K is the conic constant, A_1, A_2, A_3, A_4, are the higher order aspheric coefficients respectively. Here, the design of lenses applied up to 16th terms of aspheric coefficients.

7.2 Results and Discussions

The optimized lens configuration is shown as Fig24. Detailed structure parameters of lens were shown as Fig25 and Fig26.

There are three reference wavelengths in this system: 486.1 (F), 587.6 (d) and 656.3 (C), respectively. The features of the system were 6.464 mm total track of lens, 5.067 mm effective focal length, and 0.279 mm back focal length, 2.8 f-number, and 76° field of view. The image height was 3.96 mm, which was little more than the diagonal size of the image sensor (7.906 mm), so it can efficiently prevent the dark angle caused by the deviation of the image sensor and optical axis. The structure of lens was six plastic lenses, included a glass infared cut-off filter (IR) which can protect the imaging surface. The chief ray angle (CRA) is limited less than 34°.

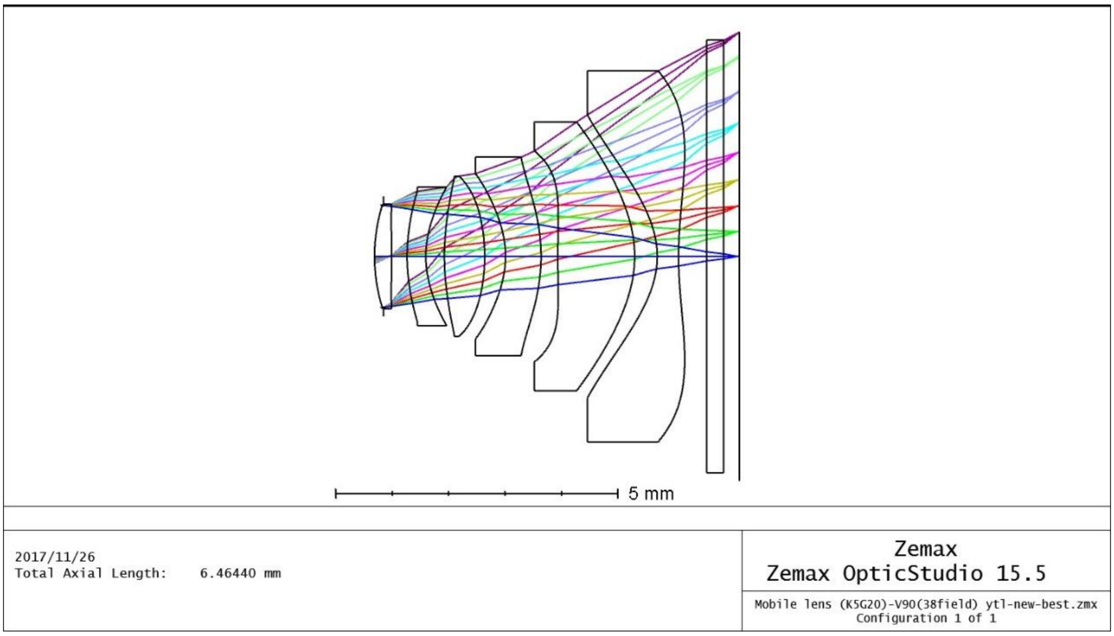

Fig 27. Optimized lens configuration

	Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic
0	OBJECT Standard		Infinity	Infinity			Infinity	0.000
1	STOP Standard		Infinity	-0.156			0.903	0.000
2	Even Asphere	Meniscus, COC	3.019	0.300	COC		0.914	-6.239
3	Even Asphere		-47.962	0.277			0.929	-1.715
4	Even Asphere	OKP4	3.125	0.331	OKP4		1.151	-9.926
5	Even Asphere		1.737	0.330			1.225	-3.404
6	Even Asphere	COC	4.541	0.713	COC		1.385	-9.049
7	Even Asphere		-3.234	0.369			1.419	0.000
8	Even Asphere	OKP4	-1.725	0.630	OKP4		1.463	-1.895
9	Even Asphere		-3.062	0.297			1.755	-9.815
10	Even Asphere	COC	14.440	1.361	COC		1.866	50.588
11	Even Asphere		-2.164	0.400			2.380	-1.926
12	Even Asphere	Field Flattener, COC	-1.568	0.378	COC		2.506	-1.715 P
13	Even Asphere		6.319	0.500			3.282	-44.660
14	Standard		Infinity	0.300	N-BK7		3.730	0.000
15	Standard		Infinity	0.279 M			3.825	0.000
16	IMAGE Standard		Infinity	-			3.971	0.000

Fig 28. Optimized lens data

2nd Order Term	4th Order Term	6th Order Term	8th Order Term	10th Order Term	12th Order Term	14th Order Term	16th Order Term
0.000	0.022	-9.405E-003	0.014	7.058E-004	-7.048E-003	1.164E-003	6.441E-003
0.000	3.429E-004	0.012	0.017	-0.013	4.047E-004	-2.870E-003	8.921E-003
0.000	-0.023	0.041	-6.779E-003	-8.959E-003	-6.313E-004	1.704E-003	4.778E-004
0.000	-0.021	0.040	-0.011	-2.142E-003	-3.683E-004	-3.342E-004	5.551E-004
0.000	-2.259E-003	-7.890E-004	4.534E-004	2.067E-005	-4.402E-005	5.170E-005	-1.387E-005
0.000	-8.769E-003	-4.238E-003	-2.968E-003	-5.103E-004	4.703E-005	3.470E-005	5.760E-006
0.000	0.018	-6.087E-003	7.402E-005	-4.218E-004	1.295E-005	7.414E-006	3.996E-006
0.000	-0.018	5.734E-003	1.809E-004	-8.269E-005	-2.591E-006	-5.495E-007	6.846E-008
0.000	-0.036	-2.187E-003	1.701E-004	-1.645E-004	3.182E-007	-8.248E-008	-4.158E-008
0.000	4.789E-003	-9.143E-004	3.299E-005	2.807E-006	-2.026E-008	-5.465E-009	-7.650E-010
0.000	6.645E-003	-4.548E-005	4.189E-006	-2.611E-007	1.038E-008	3.407E-010	-2.292E-010
0.000	-4.813E-003	-1.291E-004	-2.870E-006	4.729E-008	5.041E-009	3.247E-010	1.771E-011

Fig 29. Optimized lens data

An optical image lens system, in order from an object to an image plane, a first lens element, a second lens element, a third lens element, a fourth lens element, a fifth lens element and sixth lens element. The first lens element uses positive refractive power which can effectively reduce the total track length of the lens system.

The first lens element produced the positive astigmatism which can be balance by the rear part of system. The total track length can be effectively reduced when the refractive power of lens is large. The refractive power of second lens is negative, it can balance spherical aberration and chromatic aberration caused by the first lens element.

The fourth lens element is a concave surface facing the object-side, convex facing to the image-side. So, the aberration generated from front lens element can be corrected. Concave of the surface that can generate positive dispersion, offset negative astigmatism produced by the front lens element. The fifth lens element with positive power has a convex image-side surface. Thus, the high order aberration of the optical image lens system can be corrected, and the image resolution has been improved.

The sixth lens element with negative refractive power has a concave image-side surface, so that the principal point of the optical image lens system can be positioned away from the image plane, and the total track length of the optical image lens system can be reduced to maintain the compact size of the optical lens system. Furthermore, the sixth lens element has at least one inflection point on the image-side surface. It can effectively reduce the oblique angle at which the light is projected onto the image sensor from the off-axis field. So, the off-axis aberrations can be further corrected. In addition, when the aperture stop is disposed near third lens, a wide field of view can be favorably achieved. As the aperture stop disposed near the object, the telecentric feature is emphasized and enables a shorter track length.

The spot diagram, MTF, field curvature and distortion, lateral color, chromatic focal shift, and relative illumination can be used to evaluate the lens design. In general, the spot diagrams must fall close together if the lens form a good image. The RMS spots of all field should be less than Airy spot ($2.44 \times \lambda \times F/_{\#} = 4.08\mu m$). The RMS spot radius of fields 1-9 (FOV 0.0 to 1.0) are 3.975μm, 4.162μm, 4.310μm, 4.269μm, 3.638μm, 4.688μm, 9.289μm and 4.688μm respectively. They are a little more than the imaging needs of the sensor, except for field 8, very close to the needs of imaging. The whole field can image clearly.

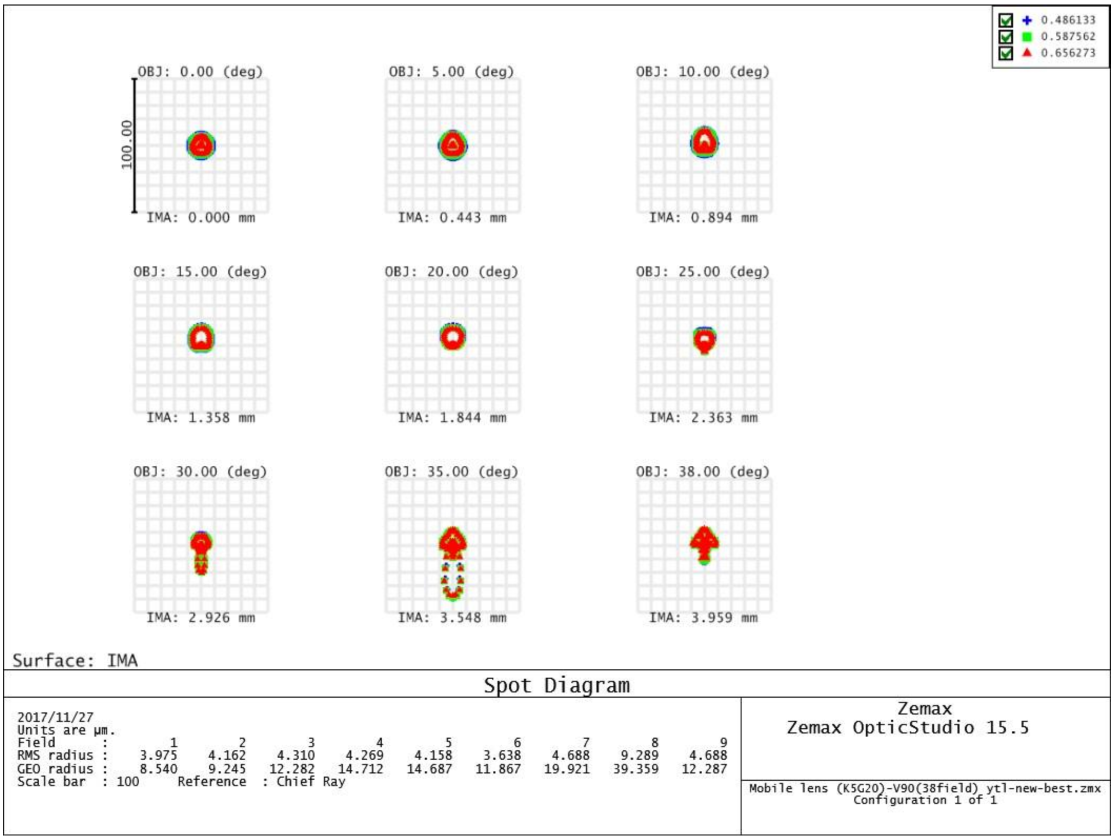

Fig 30. Spot diagram

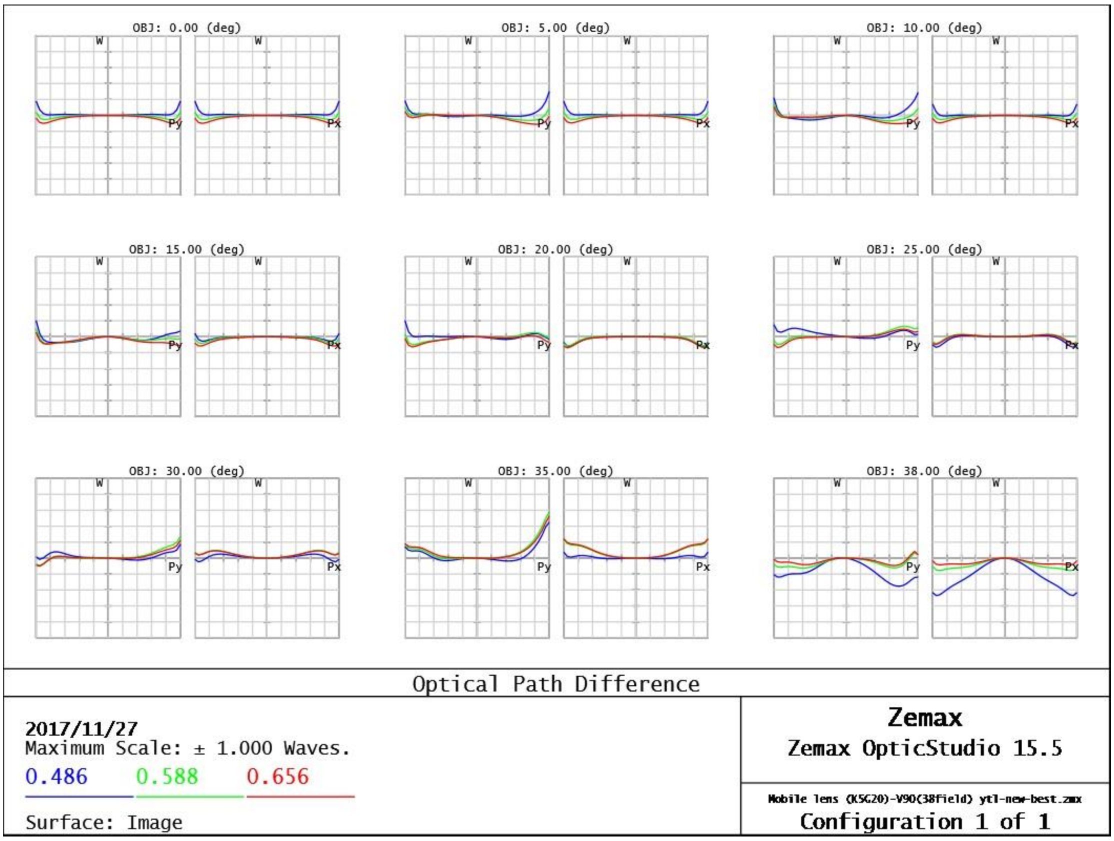

Fig 31. OPD

MTF of the optical system is a comprehensive standard to evaluate the designing of imaging system. In this design, the MTF value of central field at 223 lp/mm is 0.530951, and 0.164083 at 446 lp/mm. The MTF of larger field (field 8, 9) are below 0.1 at $355lp/mm$, at 446 lp/mm is 0.

The field curvature and distortion of the lens is shown as Fig31. The lens has the low field curvature; it is within 0.1, much less than the imaging need 0.1, and the distortion is less than 0.1%. As long as the distortion is less than 4%, the human eye will not perceive it. Design indexes mentioned above all meet the requirements. These aberrations are controlled very well.

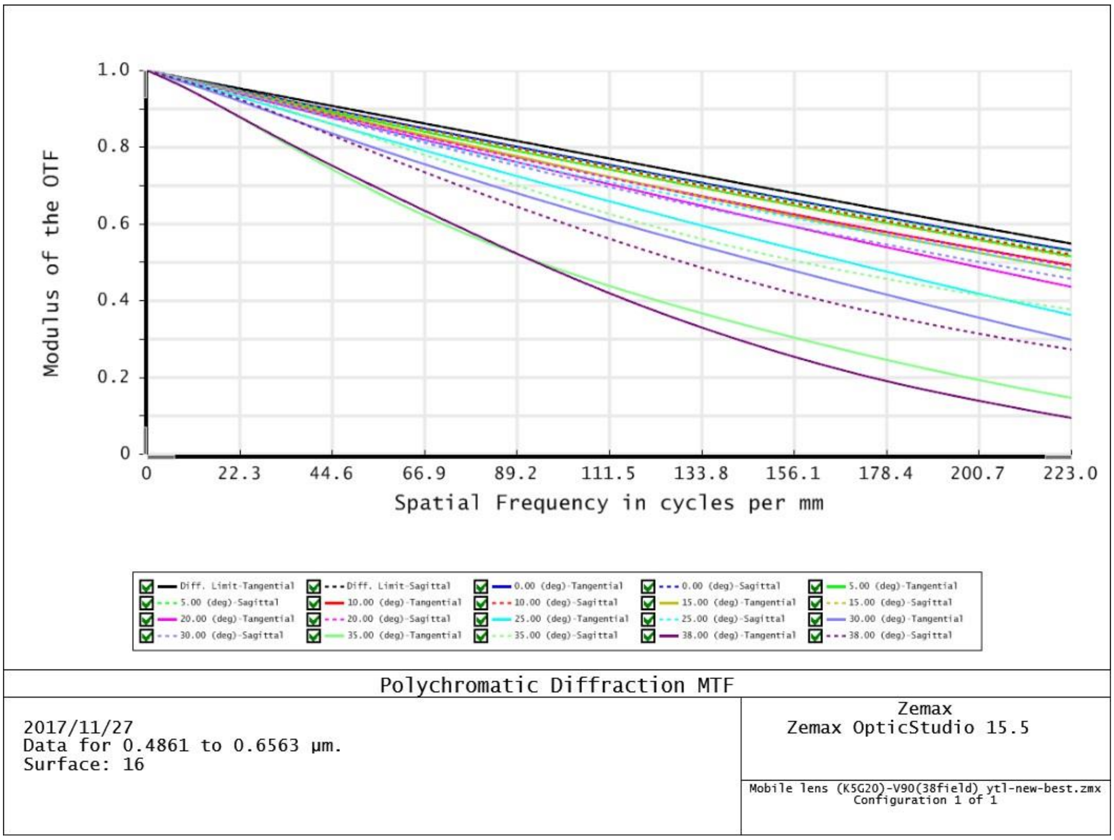

Fig 32. MTF at 223 lp/mm

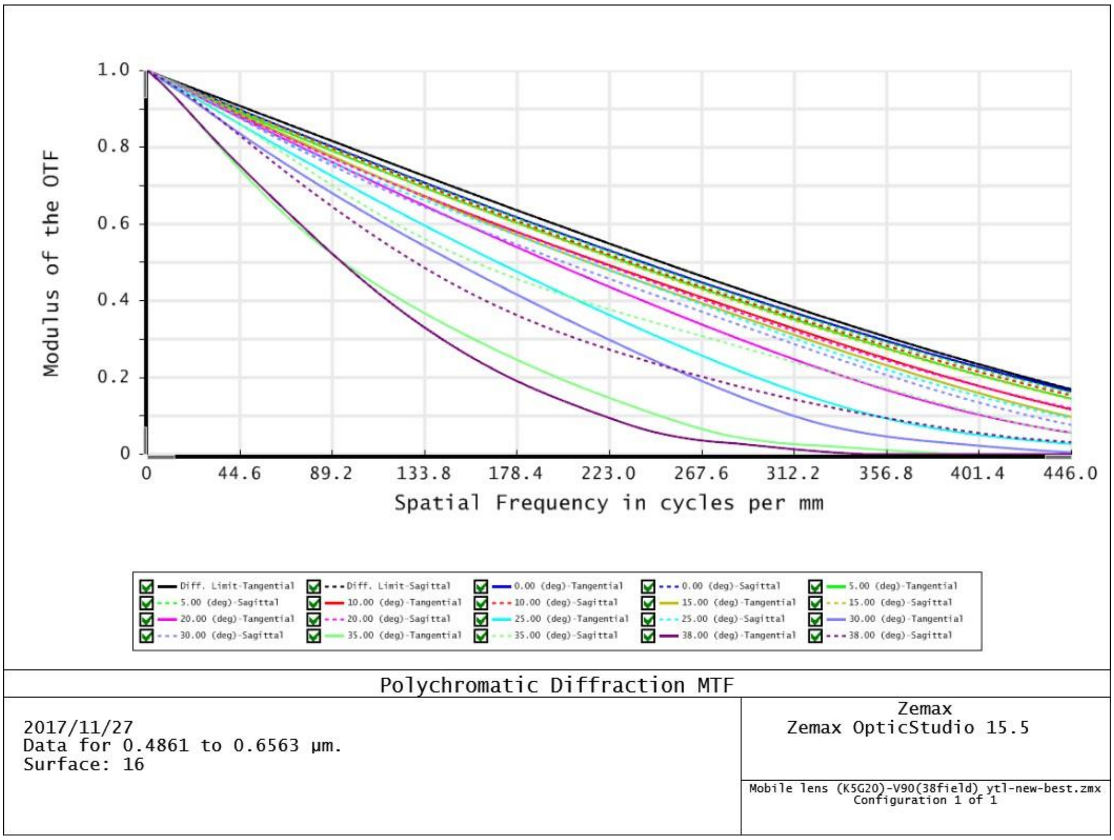

Fig 33. MTF at 446 lp/mm

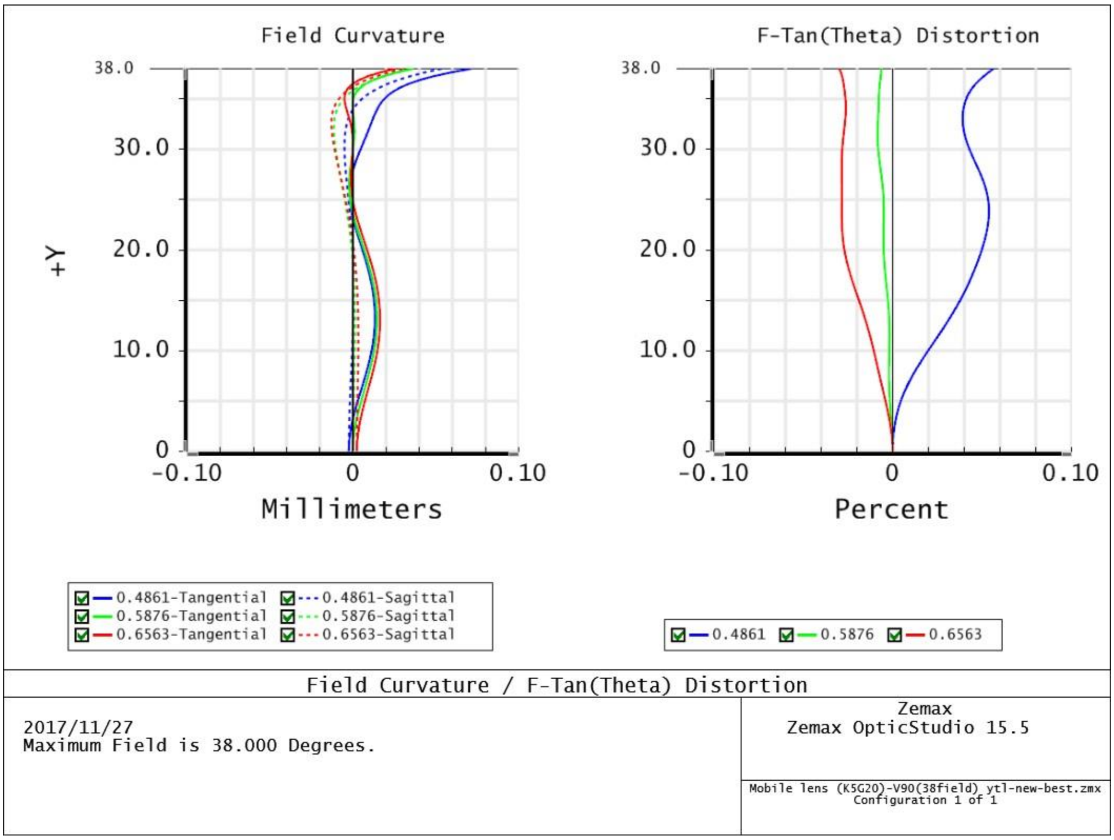

Fig 34. Field curvature and distortion

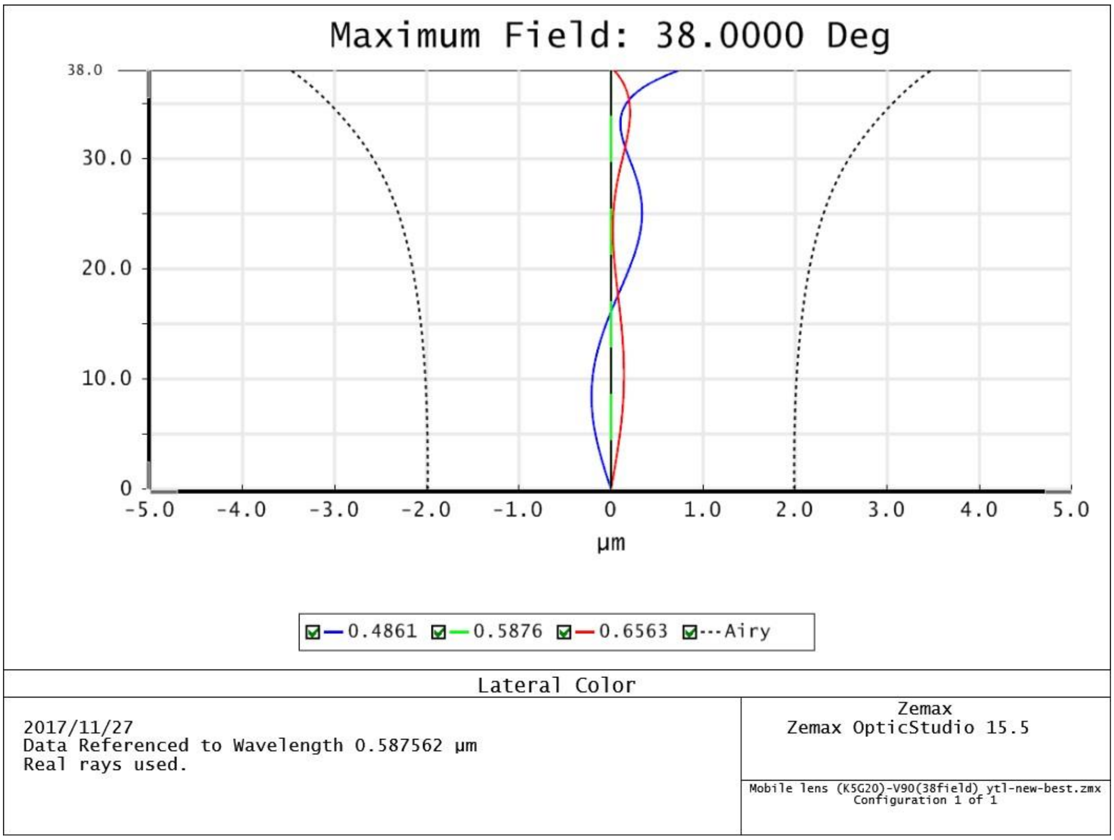

Fig 35. Lateral color

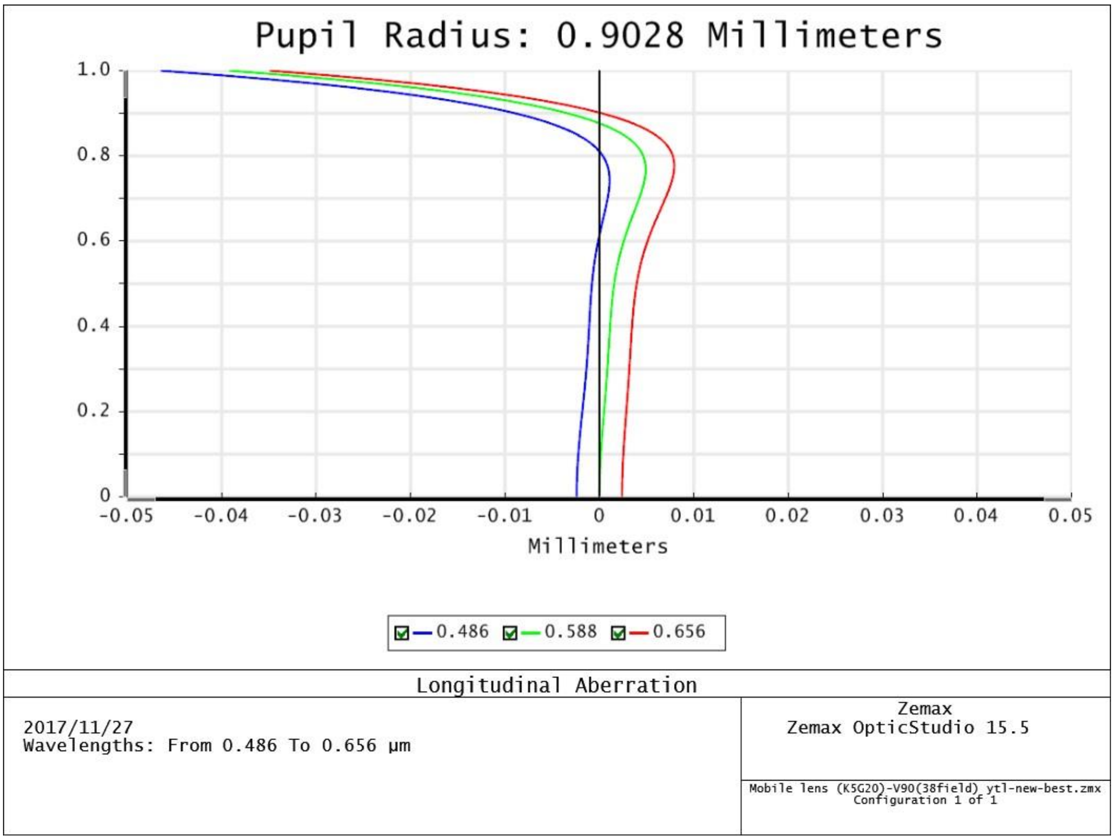

Fig 36. Longitudinal aberration

From the Fig 35 and Fig 36, the lateral color is 0.7325μm, which is smaller than the pixel size. The maximum longitudinal aberration is 39μm. The design index all meet the requirements.

Relative illumination is shown as Fig35, the minimum value is 38% at the largest field. If the illumination is too low, the marginal field will be dark, it is easily to recognize. However, an auto gain controlling circuit and an auto balance controlling circuit can keep a uniform brightness of the image.

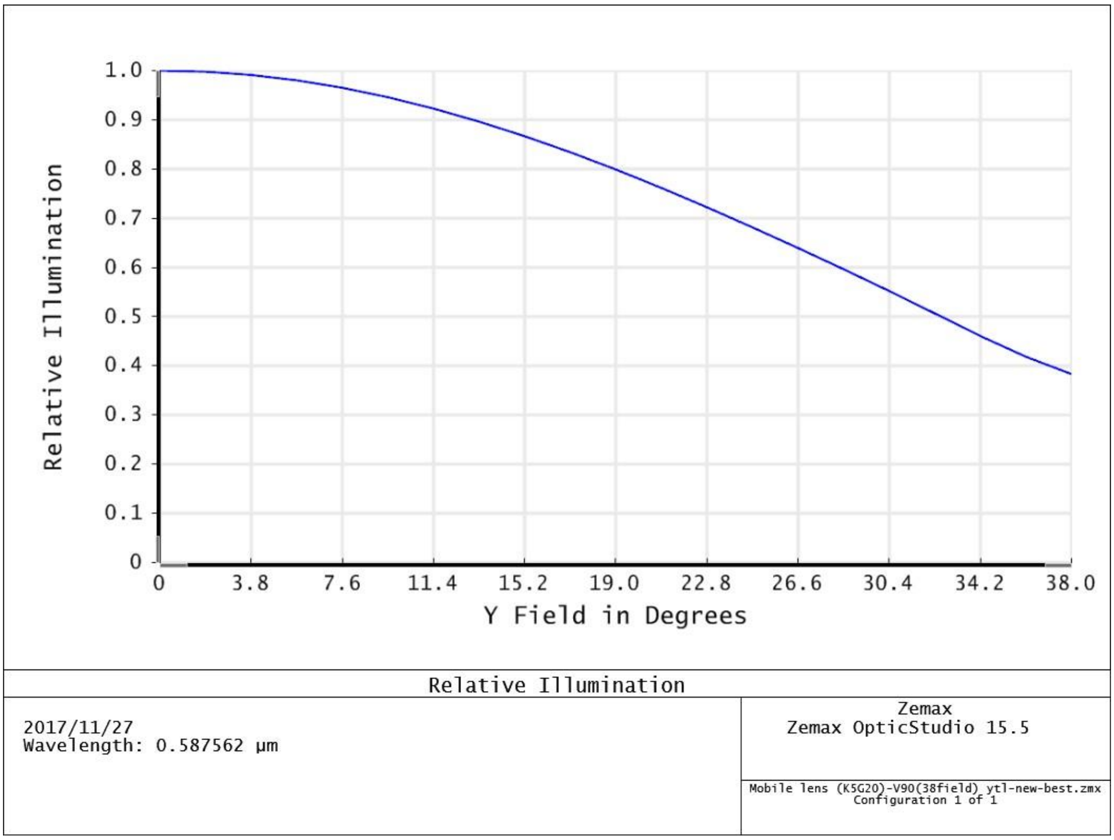

Fig 37. Relative illumination

Chief ray angle of all fields of the main wavelength is less than 34°, it meets the requirements of the image sensor. The Table6 present the chief ray angle value of all fields.

Field	Chief ray angle
1.0	32.9
0.9	33.0
0.8	32.7
0.7	31.4
0.6	28.8
0.5	25.2
0.4	20.9
0.3	16.2
0.2	11.0
0.1	5.63
0	0

Table6. Chief ray angle of field

7.3 Conclusion and Way of Improvement

By using Zemax, a 21.4 mega-pixels mobile phone lens with great image quality is designed. The lens consists six plastic aspheric lenses, and a glass filter. OV21840 with pixel size 1.12μm from Omnivsion is used as image sensor. The system has an effective focal length 5.067mm, a f-number of 2.8, a field of view (FOV) of 76°, and total length of 6.46mm. The distortion is less than 0.1%, and field curvature is less than 0.1. The result shown that the lens can meet requirements and be integrated with common mobile phone.

As the Fig29, Fig30 shown above, the MTF of large field is lower than 0.1 at 446 lp/mm. It can be improved by freeform surface based on the pedal curve to ellipse by referring to the paper “Miniature Camera Lens Design with a Freeform Surface”, “The role of aberrations in the relative illumination of a lens system”. The rear group of lens system (fourth, fifth and sixth lens) contains surfaces with different curvature direction between center of the surface and edge (e.g., concave in the center and turning back to convex before the edge). It is noted that the surface profile can be described by the pedal curve to the ellipse. The sag S(r) of this pedal surface is obtained by rotation about z-axis:

$$S(r) = b - \sqrt{\frac{b^2 - 2r^2 + \sqrt{b^4 + 4(a^2 - b^2)r^2}}{2}}$$

where a is the major axis of the ellipse, b is the minor axis, and r is the radial distance from the optical axis. A freeform surface polynomial surface can be written as

$$z_p = A_1 S_1(r) + A_2 {S_1}^2(r) + A_3 {S_1}^3(r) + B_1 S_1(r) + B_2 {S_1}^2(r) + B_3 {S_1}^3(r)$$

where $S_1(r)$ and $S_2(r)$ are two sets of pedal surfaces, $A_1 - A_3$ and $B_1 - B_3$ are coefficients. It can improve the lens system with better aberration control at large field and make the illumination on image plane more uniform.

8. Future Development of Mobile Phone Camera

In the past years, the mobile phone with camera exploded to hit the market. Resolution starts from 0.11 MP to 21 MP, even 41 MP, as the advanced semi-conductor technology gradually improved. The pixel size greatly scaled down to 1µm. In 2017, the year of dual-camera phones, the flagship smartphone of every companies has two lenses in the rear camera, such as Samsung Note 8, iPhone 7 plus, iPhone 8 plus and iPhone X in the late 2017. It is hard to find a flagship smartphone without the second lens than with. The mobile phones with dual-camera are expected to keep improving the image quality and become popular for several years.

However, as the mobile camera phone with single camera turn to dual-camera, the technology of image sensor keeps improving for providing high image quality to meet the high-quality camera lens system. For example, the image sensor with QuantumFilm technology invented by InVisage provide a high image quality by using the quantum dots rather than silicon of traditional CMOS image sensor. It can increase high-dynamic-range imaging and provide more details of picture.

QuantumFilm is a photosensitive layer that relies on newly materials to absorb light; the newly material is made up of quantum dots, nanoparticles that can dispersed to form a grid once they are synthesized. QuantumFilm absorbs the same amount of light as traditional silicon layer, but it is ten times thinner than traditional layer. Because of silicon's indirect bandgap, light must pass through a thick layer of silicon before it can pass its energy to silicon's electrons, and then this leads to less efficient transfer of energy from light to semi-conductor. The QuantumFilm's bandgap is direct, so light passes its energy rapidly and efficiently to the electrons in QuantumFilm. This leads a fast and efficient rate of conversion of light to an electrical signal.

In a QuantumFilm pixel, light passes through the color filter array, and is then detected by the quantum dots in the QuantumFilm layer. The metal wiring represents the sensor's electrical circuitry. The higher positioning of the photosensitive layer allows the QuantumFilm pixel to detect more photons, store more electrons, and therefore more photographic information. Then, produce colors more accurately and fit into a thinner camera module.

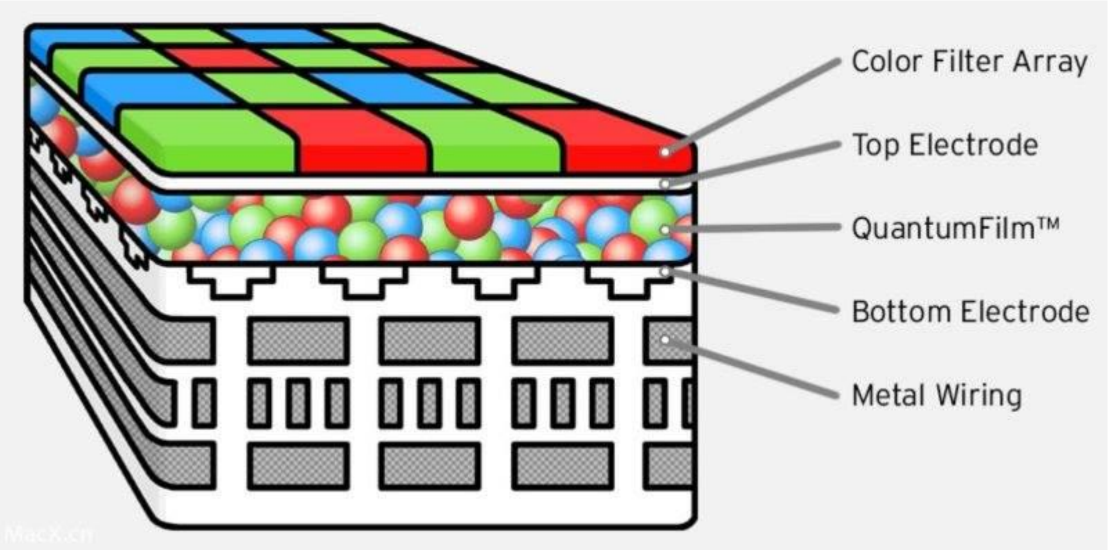

Fig 38. Sectional structure of image sensor with QuantumFilm technology

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