Journal of the Optical Society of Korea, Vol. 1, No. 2, September 1997, pp. 74-80

Telephotolens Design With Refractive/Diffractive Hybrid Lens

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(Received: July 9, 1997)

300mm F/4.0 telephotolens with diffractive hybrid lens was designed, and its optical performance was tested and compared with a traditional lens system. DOE(Diffractive Optical Element) reconstructs wavefronts using wave phenomena of light to focus the incident light onto the focal point and has negative Abbe number while a traditional lens uses geometrical phenomena of light and has positive Abbe number. Therefore, a diffractive hybrid lens containing both refractive and diffractive elements can remarkably correct chromatic aberration and spherical aberration of an optical system. We investigated and analyzed the optical properties of a diffractive hybrid lens for the visible spectrum, and we used a diffractive hybrid lens to design and evaluate a 300mm F/ 4.0 telephotolens without the special LD(Low Dispersive) glass lens which is costly and difficult to manufacture. Most traditional telephotolenses use the special LD glass for chromatic aberration correction. Optical performance tests such as resolution and characteristics of aberration of both lens systems using a diffractive hybrid lens and traditional lens were performed.

I. INTRODUCTION

The Diffractive hybrid lens containing both refractive and diffractive elements is one of the significant applications of DOE(Diffractive Optical Element) which uses diffraction properties of light. A conventional all refractive lens system needs 2 or 3 lenses to correct chromatic and spherical aberration. But if a diffractive hybrid lens is used, the same or much better chromatic and spherical aberration correction can be achieved with a single diffractive hybrid lens. This diffractive element is called K.E.(Kinoform Element), or HOE(Holographic Optical element) because it uses phase modulation like holography. Of course, an aspheric lens also can reduce the number of lenses in an optical system, but it mainly corrects spherical aberration. The diffractive hybrid lens has been used in many MWIR(Middle Wavelength Infrared), LWIR(Long Wavelength Infrared) and diffraction limited laser optical systems because it has excellent optical properties in the IR and narrowband spectral region optical systems.

The diffractive hybrid lens also can be used in broadband visible spectrum optical system to reduce the weight and size of the optical system, by reducing the number of lenses and to replace the costly and hard to manufacture LD(Low Dispersive) glass used in the telephotolens. Therefore, many research activities are taking place to apply the diffractive hybrid lens to telephotolens system, optical systems for space exploration and very simple compact single focus or zoom lens systems for CCD applications. To apply the diffractive hybrid lens in broadband visible spectrum optical systems, the stray ray problem induced by 0th and higher order diffracted rays excepting for 1st orders should be considered. Those stray rays fall on unwanted points of the image plane and may blur the image. This problem is due to the reduction of the 1st order diffraction efficiency in the broadband spectral region. To make a good image quality, average 1st order diffraction efficiency over the bandwidth of spectrum should be above 90 %.

In this paper we're going to investigate the main optical properties of a diffractive hybrid lens in relation to its characteristic for chromatic and spherical aberration correction. And through the design and analysis of a 300mm F/4.0 telephotolens with a diffractive hybrid lens, we are going to show that the designed telephotolens with diffractive hybrid lens has much higher MTF values and better geometrical aberrations than those of conventional telephotolens. Thus, use of a diffractive hybrid lens in a telephotolens is a better solution than traditional design methods using special LD glass.

II. FUNDAMENTAL THEORY OF THE DIFFRACTIVE HYBRID LENS

The basic theory behind the K.E. of the diffractive hybrid lens is almost the same as the explanation of the lens function of a Fresnel zone plate. But, there is

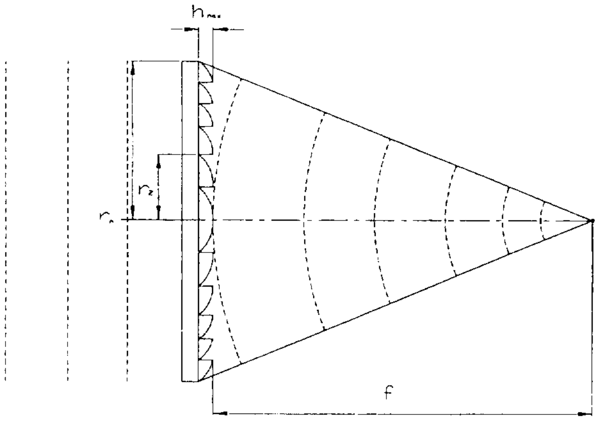


FIG. 1. Schematic diagram of surface profile of K.E. and wavefronts reconstruction by the K.E.

a main difference between those two optical elements. The Fresnel zone plate only controls the optical path lengths of diffracted light for each opaque zone to get an appropriate focal point through the modulation of opaque zone radii. So, it makes amplitude modulation of wavefronts, and it has 2-dimensional structures, but the diffractive element of the diffractive hybrid lens, K.E. controls optical paths for each surface profile not only by radii of surface profiles but also by refractive index modulation according to the height of each surface profile. For this reason, one can call this diffractive element HOE, which makes phase modulation of wavefronts.

The Fig. 1 is a schematic diagram representing the surface profiles of K.E. and reconstruction of wavefronts by K.E. to make a focus of the wavefronts on point F.

In this case, r_n, the radius of each zone profile is

$$r_n = \sqrt{2n\lambda_0 f}\ , \tag{1}$$

where λ_0 is the wavelength of the wavefronts , f is the focal length of K.E. and n = 1,2,3$\cdots$. This Eq.(1) is the same as the equation describing the lens function of a Fresnel zone plate. For each zone, the optical path difference between focal point F and the top of the zone is $f + n\lambda_0$ to make the following condition, $r_n^2 = (f + n\lambda_0)^2 - f^2$. We can obtain Eq.(1) from this condition and the paraxial approximation, $n\lambda_0 < 2f$. For K.E., the maximum zone profile height, h_m is

$$h_m = \frac{\lambda_0}{(n(\lambda_0) - 1)} \tag{2}$$

Eq.(2) is regarded as a refractive index modulation to make continuous phase matching for adjacent zone profiles and within a zone profile through phase delay introduced by the refractive index of K.E. material. The radial symmetry function, $\Phi(r)$ for wavefronts in Fig. 1 is then expressed as

$$\Phi(r) = \frac{2\pi}{\lambda_0}[\mathrm{A}_1 r^2 + \mathrm{A}_2 r^4 + \mathrm{A}_3 r^6 + \cdots], \tag{3}$$

where $\mathrm{A}_1 = -\frac{1}{2f}$, $\mathrm{A}_2 = \frac{1}{8f^3}$ and $\mathrm{A}_3 = -\frac{1}{32f^5}\ldots$.

The above descriptions are the basic theory of K.E. This K.E. is combined with a conventional lens to make a refractive/diffractive hybrid lens. The main advantage we can expect from adoption of K.E. in an optical system is that K.E. has an excellent chromatic aberration correction function. This is because K.E. has a negative of Abbe number whereas a conventional refractive optical element has positive. The analysis of this optical property of K.E. was started from Sweatt model[1] which describes the Abbe Number of K.E., ν_D as

$$\nu_D = \frac{n(\lambda_0) - 1}{n(\lambda_S) - n(\lambda_L)}\ , \tag{4}$$

where λ_S and λ_L are the shortest and the longest wavelength in the spectral bandwidth of K.E., and each n represents the equivalent refractive index at each wavelength. Using the Sweatt's modeling, Eq.(4) reduces to Eq.(5).

$$\nu_D = \frac{\lambda_0}{\lambda_S - \lambda_L}\ . \tag{5}$$

The Abbe number for a conventional refractive element is given by Eq.(6), exactly the same form as Eq.(5).

$$\nu_R = \frac{n(\lambda_0) - 1}{n(\lambda_S) - n(\lambda_L)} \tag{6}$$

Fig. 2 is a schematic diagrams of a conventional refractive lens, diffractive K.E., refractive/diffractive hybrid lens and resulting chromatic aberration.

For the diffractive hybrid lens, the total optical power is

$$\varphi_{tot} = \varphi_{\mathrm{Refractive}} + \varphi_{\mathrm{Diffractive}} \tag{7}$$

From Eq.(7), the focal length of each element of the hybrid lens is given by Eq.(8), the achromatic condition.

$$f_R = (1 - \frac{\nu_D}{\nu_R})f_{tot},\quad f_D = (1 - \frac{\nu_R}{\nu_D})f_{tot} \tag{8}$$

Thus, for the refractive/diffractive hybrid lens used in the broadband spectral region, Eq.(1) can be also expressed as follows.

$$r_n = \sqrt{2n\lambda_0(1 - \frac{\nu_R}{\nu_D})f_{tot}} \tag{9}$$

For most visible imaging optical systems, the spectral region is defined between 435.8 nm(g-line) and 656.3 nm(C-line) and the central wavelength λ_0 is set to 587.6 nm. In this case, the Abbe number of the diffrac-

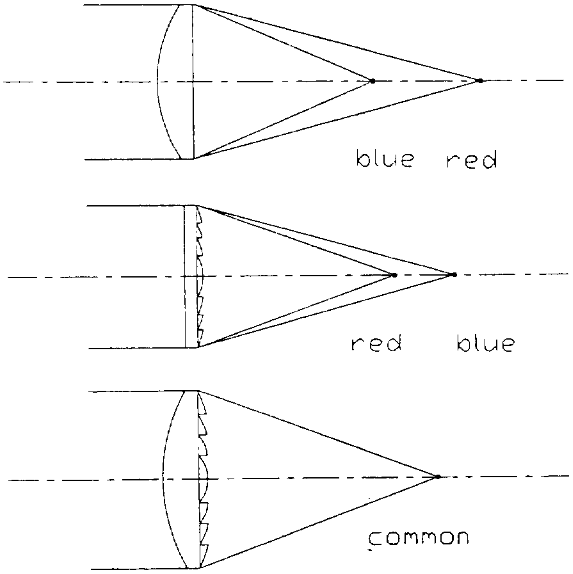


FIG. 2. Schematic diagram of conventional refractive lens, diffractive element (K.E.) and refractive/diffractive lens.

tive element and the refractive element have values of -2.664853 and 20~85, respectively. Thus it is apparent that the optical power portion of the diffractive element in the diffractive hybrid lens is much smaller than the refractive element's in the broadband visible spectral region according to Eq.(8). At this point, we can figure out that this feature of the diffractive element allows for the achromatization of hybrid lenses with diffractive elements which are of long focal length and have a high aperture[2] since the negative Abbe number of the diffractive element allows optical designers to design the refractive/diffractive hybrid lens which has the characteristic that the power of the refractive element is close to the total conventional achromat doublet power and much smaller than the power required in the all glass doublet[3] when the conventional achromat doublet is replaced with a diffractive hybrid lens. This means that we can reduce the surface curvature of the refractive element of the hybrid lens to get much higher aperture size than a conventional doublet's. Furthermore, this feature allows monochromatic aberrations of lens such as spherical aberration or coma to be corrected much better than conventional refractive doublet or combination of lenses. In spite of all these advantages expected from this refractive/diffractive hybrid lens, there is a severe problem limiting the use of hybrid achromat. That is the secondary spectrum for achromat doublet lens defined by Eq.(10) [3].

$$SchC = -\frac{y_a}{u_k'^2}\,\phi\,\frac{P_1 - P_2}{\nu_1 - \nu_2}, \qquad (10)$$

where y_a is the axial ray height at the lens, u_k' is the final slope of the axial ray to the image point, ϕ is the power of the lens, p is the partial dispersion of each lens material, and ν is the Abbe number of each lens material. The DOE hybrid has about five times the secondary spectrum compared with a typical conventional refractive doublet, and this limits the wavelength bandwidth of the hybrid doublet.[3] This means that the broader the wavelength bandwidth of the diffractive hybrid lens, the larger the secondary spectrum.

The spherical aberration induced by the refractive element can be corrected by the diffractive element when the third order aberration is equivalent to the wavefront aberration.[4] This can be explained by the following example. Generally, many diffractive hybrid lenses have a shape of convex plano lens. This is because the early manufacturing process for diffractive hybrid lens is done by photolithographical methods for which it is very difficult to introduce the K.E. surface profiles on a curved surface. Therefore, the application of a diffractive hybrid lens is restricted to the hybrid lens which has such a shape. Now, let's assume that the diffractive hybrid lens has a convex plano shape like Fig. 2-(c). In this case, if we consider only third order aberration, the longitudinal spherical aberration can be expressed by eq (11) for the convex plano lens.[4]

$$W_{spherical} = \frac{(n^3 - 2n^2 + 2)f}{128\lambda_0 (n^3 - 2n^2 + n)(F/\#)^4} \qquad (11)$$

Then, spherical aberration induced by the refractive element can be corrected by the diffractive element which has the same number of zone profiles as the number of wavefront aberration given by eq (11) because every zone profile controls the phase delay of one wavefront. Generally the coefficient of r^4 in Eq.(3) is directly related with the third order aberration.

For the K.E. of a diffractive hybrid lens, the main diffraction order is the 1st order, any other diffraction order's lights are acting as stray rays which blur the image on the focal plane. This stray ray is the main problem for application of the diffractive hybrid lens in a broadband spectral lens system. Especially for film camera lenses, those stray rays make fog- like dots in developed photograph if the average diffraction efficiency over the spectrum region of the diffractive hybrid lens is controlled to have low value. The 1st order diffraction efficiency of K.E. for certain λ is

$$\varepsilon_1 = \left[\frac{\sin\pi\left[\frac{\lambda_0}{\lambda}\left(\frac{n(\lambda)-1}{n(\lambda_0)-1}\right) - 1\right]}{\pi\left[\frac{\lambda_0}{\lambda}\left(\frac{n(\lambda)-1}{n(\lambda_0)-1}\right) - 1\right]}\right]^2 \qquad (12)$$

Eq.(12) is the calculation for the K.E which has continuous surface profiles like Fig. 2(c). If K.E. is manufactured by photolithographical methods, the equivalent Eq. of Eq.(12) for the multileveled K.E.like Fig. 3 (approximated shape of continuous surface profile) is Eq.(13).

FIG. 3. Schematic diagram of multilevel K.E. surface profile as approxiamtion of continuous shape, the surface profiles are quantized to have N number of levels (In this diagram, N is 4).

$$\varepsilon_1 = \left[\frac{\sin\frac{\pi}{N} \sin[\pi(\frac{\lambda_0}{\lambda}\frac{n(\lambda)-1}{n(\lambda_0)-1}) - 1]}{\pi \sin[\frac{\pi}{N}(\frac{\lambda_0}{\lambda}\frac{n(\lambda)-1}{n(\lambda_0)-1}) - 1]} \right]^2 \tag{13}$$

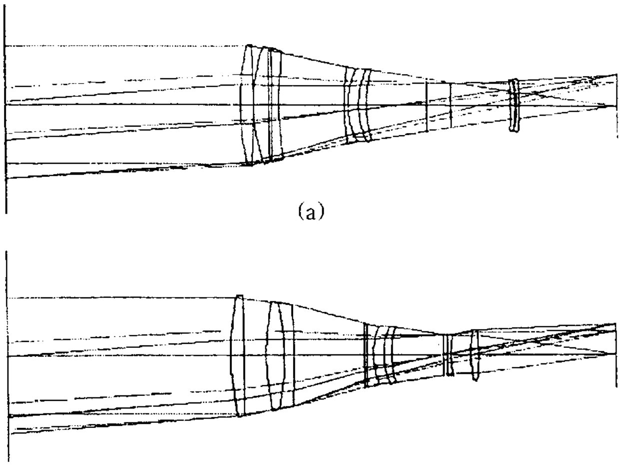
If N goes to infinity, the Eq.(13) becomes Eq.(12). With these, we can see that if K.E. is manufactured by photolithographical methods, the 1st order diffraction efficiency of the K.E. is lower than continuous profile K.E.'s., As explained above, to apply K.E. into a broadband spectral lens system, a large amount of average 1st order diffraction efficiency over the spectral region is required. Generally a value is above 90%. For this, at least 8 are required for the K.E. if photolithographical methods are used. The average 1st order diffraction efficiency can be obtained by taking the integral of Eqs.(12) and (13) over the spectral bandwidth. Thus, it depends on its spectral bandwidth, $(\lambda_S - \lambda_L)$ and designed central wavelength, λ_0 in Eq.(5). Since the function is given in the form of a Sinc function, the 1st order diffraction efficiency in the region of short wavelength has a relatively low value and it has a relatively high value in the region of long wavelength.

III. THE CONVENTIONAL TELEPHOTOLENS WITH LD GLASS LENS

Most conventional telephotolenses include the special LD(Low Dispersive) glass lenses which are costly and difficult to manufacture because the optical scheme of the telephotolens is similar to a positive achromat's. A positive achromat comprises a strong positive element of low dispersive glass lens and a weak negative element of high dispersive glass lens. Most LD glasses used in telephotolenses are regarded as special glass because the cost of the glass is almost 30 times more expensive than BK7, the most general glass from Schott Co., and they are hard to manufacture due to its physical properties. Fig. 4(a) is the ray tracing diagram of 300mm F/4.0 telephotolens with the lens specification for infinity conjugation shown in the Table 1. The special LD glass is FK52 which has refractive index for d-line of 1.48605 and Abbe number of 81.80.

IV. TELEPHOTOLENS DESIGNED WITH A DIFFRACTIVE HYBRID LENS

The main target of the use of diffractive hybrid lens for our telephotolens is to eliminate the special LD glass, FK 52 lenses in the conventional design. For this, we introduce the convex plano shaped diffractive hybrid lens which has its K.E. on plane surface. At the starting point, the optical performance specs. are based on the conventional telephotolens system. The result of this design allows the lens system with the diffractive hybrid lens to have much better optical specifications shown in Table 1.



(a)

(b)

FIG. 4. (a) The ray tracing diagram of conventional 300mm F4.0 telephotolens. The first 2 lenses are FK 52 LD glass lenses.(b) The ray tracing diagram of 300mm F4.0 telephotolens with refractive/diffractive hybrid lens. The first lens is refractive/diffractive hybrid lens.

Fig. 4(b) is ray tracing diagram of the telephotolens with diffractive hybrid lens. The first lens in Fig. 4(b) is the refractive/diffractive hybrid lens having diffractive element on its plane surface; glass of the lens is BK7. The focal length of this diffractive element itself is 10757.01 mm whereas the focal length of the refractive surface is 289.088 mm, and the total focal length of refractive/diffractive hybrid lens is 281.665 mm. And the Abbe number of diffractive element and refractive element in this case is

$$v_d = \frac{546.1}{435.8 - 656.3} = -2.471041.$$

The value of ν_R , the refractive index of BK7 for e-line is.

$$\nu_R = 63.96.$$

Then $\Phi(r)$ in Eq.(3) for this diffractive element is

$$\phi(r) = \frac{2\pi}{0.0005461}[(-4.648132 \times 10^{-5})r^2 + (1.170634 \times 10^{-8})r^4 - (1.6711335 \times 10^{-12})r^6]$$

And this function of wavefront at the surface of the diffractive element is shown in Fig. 5.

In this case, the 6th order of r is enough to get the

TABLE 1. The optical specifications of conventional telephotolens with two special LD glass lenses and telephotolens with diffractive hybrid lens.

Optical specification	Conventional optical system	Optical system with diffractive hybrid lens
Focal length, F/#	291 mm, F/# 4.12	290 mm, F/# 4.0
Resolution(MTF)	Tangential MTF at -0.09 mm defocus	Tangential MTF at 0.01 mm defocus
On Axis:	37 %(at 100 lps/mm) 60 %(at 50 lps/mm)	58%(at 100 lps/mm) 75%(at 50 lps/mm)
0.7 Field:	25%(at 100 lps/mm) 56%(at 50 lps/mm)	46%(at 100 lps/mm) 69%(at 50 lps/mm)
0.1 Field:	10%(at 100 lps/mm) 25%(at 80 lps/mm) 48%(at 50 lps/mm)	38%(at 100 lps/mm) 50%(at 80 lps/mm) 63%(at 50 lps/mm)
Half angle of FOV	± 4.2 degree	± 4.21 degree
Color weighting factors	C(0.3),d(1.0),e(0.8),F(0.7),g(0.3)	C(0.3),d(1.0),e(0.8),F(0.7),g(0.3)
Vignetting	51 % at 0.1 field	50 % at 0.1 field
Distortion	< 1.2%	< 1.5%
The nearest object distance	2.5m	1.2m
Used glasses	Schott glasses; FK52 [a] ,. SF15, F5 and LaK8	Schott glasses; BK7,FK5,SF10, F3 and LLF7

[a] The special LD glass, FK52 which has refractive index at d-line, 1.48605 and Abbe number, 81.80

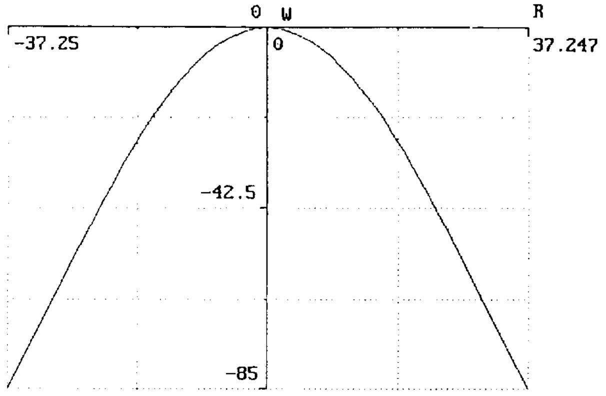


FIG. 5. The wavefronts function in the scale of wavelength (546.1nm) vs. clear aperture of K.E. surfaces.

proper wavefront function and it is important that the 546.1nm is chosen as λ_0 whereas the main wavelength for the whole optical system is 587.6 nm. This shift of designed central wavelength for the diffractive element is done because we can get much higher 1st order average diffraction efficiency in the region of 430 nm. As described before, the average 1st order diffraction efficiency function over wavelength is a Sinc function and it has the minimum value in the region of shortest wavelength of the spectral bandwidth. But if we shift the designed central wavelength of K.E. to a little shorter wavelength, then the 1st order diffraction efficiency in the region of short wavelength can be a little higher value.[5] The 1st coefficient in $\Phi(r)$, -4.648132 is exactly matched with 1/(2f) according to Eq.(3) whereas the 2nd and 3rd coefficients for r^4 and r^6 in the above function are larger than $1/(8f^3)$and $1/(32f^5)$. This is because Eq.(3) is a paraxial approximation form using the condition $n\lambda_0 \ll 2f$. and for the diffractive element designed for monochromatic optical system. But in the practical case, the coefficients for r^4 and r^6 have higher values than the values in Eq.(3) to consider real aberrations such as spherical aberration, coma and real color weighting factors for the design of a diffractive element working in the broadband spectral region.

The depth of zone profile given by Eq.(2) is

$$h_m = \frac{0.0005461}{1.51872 - 1} = 0.001053\text{mm} ,$$

where 1.51872 is the refractive index of BK7 for e-line. Then the ideal depth of zone profile are 1.053 μ m and the specifications related with the physical shape of zone profiles of the diffractive element are shown in Table 2. The average 1st order diffraction efficiency of the diffractive element which has 8-level-zone profile is 90.32%. This is high enough value to reduce the stray ray problem which may affect the image quality of a lens system with a diffractive element. The distribu-

TABLE 2. The specifications for the physical shape of zone profiles.

Number of zones	86
The first zone radius	3.4326 mm
The $86^{'th}$ zone radius	37.2468 mm
Number of levels	8
Depth of each zone	1.053 μ m

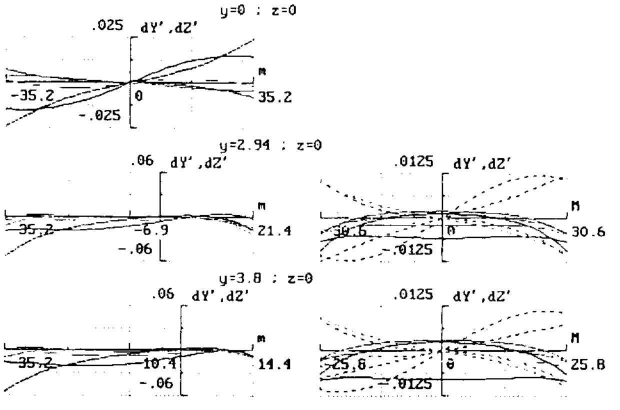
TABLE 3. Distribution of diffraction efficiencies of the diffraction element.

Wavelength	3'rd order	2'nd order	1st order	0'th order	-1st order	-2'nd order	-3'rd order
435.8nm	1.40 %	9.10 %	74.0 %	3.90 %	1.40 %	0.78 %	0.55 %
486.1nm	0.34 %	1.80 %	90.0 %	1.40 %	0.43 %	0.23 %	0.15 %
546.1nm	0.00 %	0.00 %	95.0 %	0.00 %	0.00 %	0.00 %	0.00 %
587.6nm	0.01 %	0.40 %	93.0 %	0.66 %	0.17 %	0.08 %	0.05 %
656.3nm	0.46 %	1.70 %	86.0 %	4.20 %	0.94 %	0.43 %	0.26 %

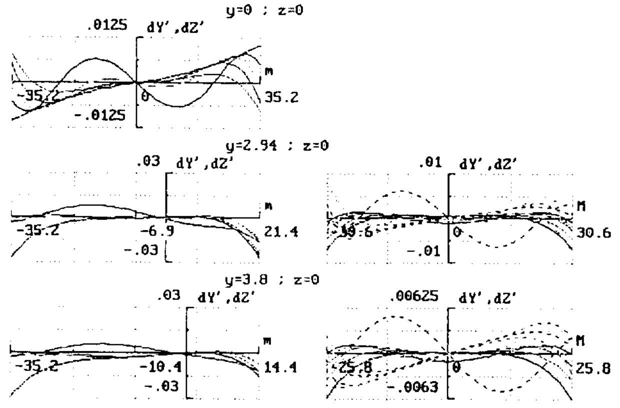
tion of diffraction efficiencies from the 0th order to ± 3rd is shown in Table 3.

V. THE COMPARISON OF OPTICAL PERFORMANCE BETWEEN TWO TELEPHOTOLENSES

The geometrical aberrations of telephotolenses with 2 LD glass, FK52 lenses and telephotolens with diffractive hybrid lens for axial field, 0.7 field and full field on image plane are shown in Fig. 6. In this figure we can analyze the geometrical aberrations for the designed wavelengths of 435.8 nm, 486.1nm, 546.1 nm, 587.6 nm, and 656.3 nm which have color weighting

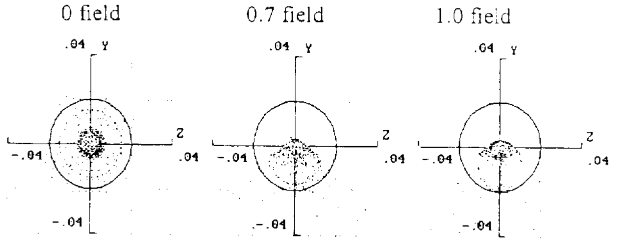


(a) Geometric aberrations of conventional telephotolens

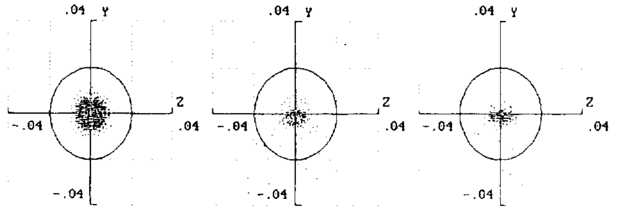


(b) Geometric aberrations of telephotolens with diffractive hybrid lens

FIG. 6. The geometrical aberrations of each telephotolens as the fields of image plane. Each y represents angle of incidnet ray to optical system.
(a) Geometric aberrations of conventional telephotolens,
(b) Geometric aberrations of telephotolens with diffractive hybrid lens.

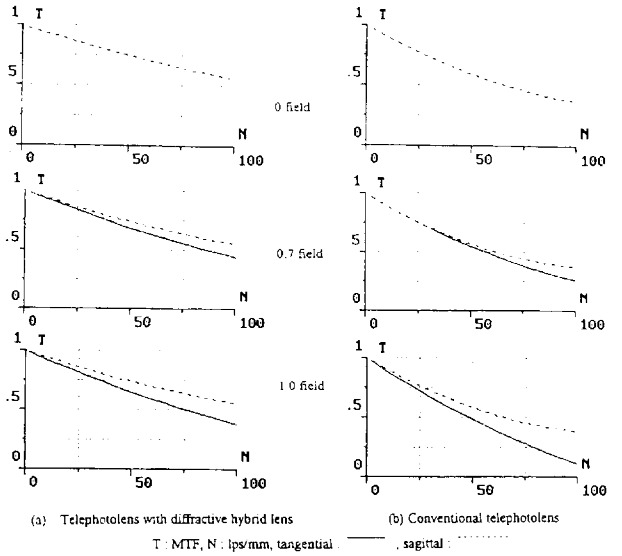


(a) Spot diagram of conventional telephotolens



(b) Spot diagram of telephotolens with diffractive hybrid lens

FIG. 7. The spot diagram of both two telehotolenses at the fields of the image plane
(a) Spot diagram of conventional telephotolens,
(b) Spot diagram of telephotolens with diffractive image plane.



(a) Telephotolens with diffractive hybrid lens (b) Conventional telephotolens

T : MTF, N : lps/mm, tangential ——— , sagittal : ·········

FIG. 8. The MTF curves of both telephotolenses, T:MTF, N:lps/mm, tangential(solid curve), sagittal(dotted curve).
(a) Telephotolens with diffractive hybrid lens,
(b) Conventional telephotolens.

factors shown in Table 1.

The axial chromatic aberration is much better corrected in the optical system with the diffractive hybrid lens, almost 2 times smaller, than for conventional optical system. This is due to the achromatization feature of the diffractive hybrid lens as described before. The spot diagrams and MTF value curves of both two systems are shown in Fig. 7 and Fig. 8.

Analyzing Fig. 7, we can see that the chromatic aberrations, the spherical aberrations, comas of the optical system with the diffractive hybrid lens are much better corrected than the conventional system's Figs. 8(a) and 8(b) show the MTF curves for the telephotolens with diffractive hybrid lens having defocus value of 0.01 mm and conventional telephotolens having defocus value of -0.09 mm, respectively. In this figure we can see that MTF values of the telephotolens using a diffractive hybrid lens are higher than conventional telephotolens' in the high frequency region. So we can see that when we apply this diffractive hybrid lens to the optical system which needs high resolution, good quality images can be obtained.

With this analysis, it is clear that the optical performance of the telephotolens with diffractive hybrid lens is much better than the conventional telephotolens. And there are no exotic or costly glass lenses, in it whereas the conventional system includes two costly and hard to work LD glass lenses.

VI. CONCLUSION

Most conventional telephotolenses use the costly and hard to work LD glass lens to correct chromatic aberration which is the dominant aberration in a telephotolens. We can design 300mm F/4.0 telephotolens using a diffractive hybrid lens without any costly or hard to work glass lenses. Since a diffractive hybrid lens has excellent feature of chromatic aberration correction, the geometrical aberrations of the optical system with a diffractive hybrid lens were reduced and we can get much better image quality and much higher MTF values than those of a conventional lens system.

VII. ACKNOWLEDGMENT

We thank to Dr. Michael.A. Gan and Mr. V. Vladimir Novoselskiy of Vavilov State Optical Institute for their support in designing the telephotolens with diffractive hybrid lens.

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