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Design of Micro Size Optical Scanner Systems

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ABSTRACT

The design and analysis of micro optical scanner systems are presented. A simulate software was implemented to study, firstly, the effects of miniaturization on the general optical properties of the system, secondly, the optical design and performance characteristics for two specific micro scanner models. These are single aperture scanner and a focal Keplerian telescopic systems, taking in consideration the performance requirements of these systems for various medical applications.

Keywords: microoptics, optical scanner, optical design

تصميم منظومات الماسحات البصريه المايكرويه

الخلاصه

يقدم البحث تصميما وتحليلا لمنظومات المسح البصرى المايكرويه . تم استخدام برنـــامج لتشبيه المنظومات البصريه , لدراسه اولا، تاثيرات صغر الحجم على المواصفات البصريه العامه للمنظومه ، وثانيا، الخصائص التصميميه والاداء لنموذجين من نماذج المسح المايكرويه. وهما ماسح المقطع الواحد، ومنظومه للمسح البصرى نوع تلسكوب كيبلر البؤري ٍذو الاشعه المتوازيه باتجاهى الجسم والصوره. تم اخذ مستلزمات الاداء لهذه المنظومـــات بنظـــر الاعتبـــار عنـــد التصميم، لتوائم مختلف التطبيقات الطبيه .

INTRODUCTION

Micro optical elements are not just a smaller version of classical optics, they provide a number of new features and a wide applications in diverse fields, such as communication systems, medical applications, and others that need specific agile beam steering systems[1,2].

Steering or scanning of optical beams could be achieved in various different methods that depend on the application[3]. For medical applications compactness, agility and high resolution are important demands. Transmissive optical scanner

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systems are preferred over reflective scanner types (that implement micro mirrors) to insure shorter light path, in other words a more compact system.

Micro size of lenses enhance agility of scanning, due to the low weight of the optical components. Besides, it is possible to get a large field of view with a small displacement of the optical components (submillimeters) [4].

In this work, and by implementing the software of ZEMAX for ray tracing[5], it was first, to study the effects of *miniaturization* on the general characteristics of an optical system. Second, *to design and analyze* two optical models of micro scanner systems. These systems are single aperture micro scanner, and Keplerian telescope afocal type micro scanner. The design criteria and the influence of various design parameters on the quality of scanned beams, that fit for various medical applications, are analyzed .

DOWNSCALING OF AN OPTICAL SYSTEM

For a lens designer scaling is trivial, at least in principle. If focal length f, lens diameter d, and other length parameters are enlarged by a factor M, the lateral aberrations ξ will be enlarged in proportion to M. However all angles and curvatures remain the same. Obvious consequences are: the size of image field $\Delta x \Delta y$ scales with M^2. The resolution δx due to diffraction does not change with M since it depends only on the wavelength λ and stop or F number $F_{\#}$ ($\delta x = \lambda F_{\#}$) [6].

The wave aberration W, which describes the deviation of the actual wavefront from a perfect spherical wavefront, scales with M, however the wavelength λ remains unchanged, hence the Strehl ratio S scales with M like:

$$S = 1 - M^2 k^2 W^2 \qquad \text{........ (1)}$$

where $k=2\pi/\lambda$. Strehl ratio is defined as the ratio of the observed peak intensity, at the detection plane of an optical system, compared to the theoretical maximum peak intensity of perfect optical design (working at diffraction limit, well corrected with neglected aberration). Alternatively, the Strehl ratio is given by:

$$S = \frac{\left|\frac{1}{\pi}\int_0^{2\pi}\int_0^1 A(\rho,\theta)\exp\{i\varphi(\rho,\theta)\}\,\rho\, d\rho\, d\theta\right|^2}{\left|\int_0^{2\pi}\int_0^1 A(\rho,\theta)\ \rho\, d\rho\, d\theta\right|^2} \qquad \text{...... (2)}$$

Where A is the normalized amplitude transmission function, and φ *is* the phase departure due to wavefront aberration function W in the exit pupil of the optical system($\varphi = 2\pi W/\lambda$). S=1 in the aberration-free case($\varphi = 0$). Characterizing the point spread function PSF by a single number, as the Strehl ratio does, will only be meaningful and sensible if the PSF is little distorted from its aberration free or ideal form. This is valid for Strehl ratio values greater than 0.8 [7].

To demonstrate the influence of scaling down optical system dimensions on the optical properties a simple aberrated thin lens is chosen as an example. Its various characteristics curves, optical path difference OPD, Modulation transfer function MTF, and Point spread function PSF with Strehl ratio, are shown in fig.1. (A) with original scale, (B) scaled down by 10, (C) scaled down by 100. Table-1 contains the original thin lens design parameters, From these results, it is clear that the system performs diffraction limited in (C), where Strehl ratio almost equal to 1.

OPTICAL DESIGN FOR TWO MODELS OF OPTICAL SYSTEMS

-Single Aperture Scanner

A single aperture microlens scanner of the type shown in fig. 2, is demonstrated for in vivo medical imaging [8] . The system is referred to as microelectromechanical MEMS system. The microlens are tilted, for scanning application by the actuation of an external AC magnetic field of flux density of the order of $22x10^{-3}$ Tesla. This is achieved experimentally by integration of micro fabricated ferromagnetic nickel platform and thermosetting elastomer microlens. The microlens material is polydimethylisiloxane PDMS to provide transmissive optical scanner with light weight.

The designed single aperature scanner system, includes two blocks located after the microlen. The first is silicon wafer and the second block is a glass sheet used to protect the CCD camera applied to capture laser light at the final image plane.

Results of the ray tracing program using the wavelength of 1.064μm are illustrated in fig.3(a,b,c). Three scanning angles of the microlens are shown, these are $-11.5^o,0^o,+11.5^o$.

The system parameters for three cases studied are given in table-2. In the first case, where the wavelength 1.064μm is applied, the total track of light is7.4mm. Since the $F_\#$ in this case is large (due to the large value of focal length f=5.2mm), Airy disc diameter is large and diffraction limit spatial frequency is very low that corresponds to a maximum resolution of 16μm[see fig.4].

When applying a different wavelength of λ=0.532μm and keeping all other parameters fixed, as in case two, the overall track of light is reduced to a value of 5.53mm, as shown in fig.5(A). However, aberrations are increased noticeably. But cutoff frequency at diffraction limit is higher in this case, deduced from the modulation transfer function MTF curve shown in fig.5(A)e, which agrees with the calculated value. A great enhancement occurs in all characteristics parameters if the entrance pupil diameter changes from 0.3mm to 0.15mm, which is the third studied case, as shown in fig.5(C) . But cut off frequency decreased, which is very low for medical applications. Here overlapping occurs between Airy discs.

AFOCAL TELESCOPIC MICRO SCANNER

The schematic of Keplerian telescopic afocal type scanner system is demonstrated in fig.6.This achieved by decentering the middle field lens 2 and the last eyepiece lens 3 with respect to the axis of the first objective lens 1[9]. This leads to the tilting of the light beam from its on- axis propagation by an angle:

$$\tan\theta = r_o / f \qquad \text{……. (3)}$$

where r_o= decentration value and f is the focal length. The focal length f are taken to be equal for all three lenses, due to a design criteria evaluated using [3×3] matrix ray propagation through an off-axis optical system. The middle lens 2, and the last lens 3 could be made shareing the same substrate , that would simplify the displacement of these lenses together. The substrate material could be a glass or other suitable material that follows the design parameters of the system. In this study glass is implemented in the design.

The systems designed and studied in this section are of two types according to the adopted $F_{\#}$ **s**, which are $F_{\#}$ 5 and $F_{\#}$ 1.5 . A comparison is made between the two designs considering the design criteria and qualifications of the two systems . In table-3 , the various design parameters of the scanner of $F_{\#}$5 is given . Table-4 contains the design parameters of the scanner of $F_{\#}$ 1.5.

In fig.7(A) the scanning angles of the system with $F_{\#}$ 1.5 are 7.69^o, 11.46^o, and 15.12^o corresponding to a decentration r_o of 0.02mm, 0.03mm, and 0.04mm respectively (only the last angle is shown). This enables an angular field of view of 30^o.

The total track of light in this case is 0.99mm. In fig.7(B) the scanning angles of the system with $F_{\#}$ **5** are 2.29^o, 3.43^o , and 4.57^o corresponding to a decentration r_o of 0.02mm, 0.03mm, and 0.04mm respectively(only the last angle is shown). The maximum scan angle is 4.57^o x 2 = 9.14^o, that represents the angular field of view of the system. The total track of light is 2.5mm. In fig. 8 the characteristics curves of the system with $F_{\#}$ 5 is shown. While the characteristics curves of the system with $F_{\#}$ 1.5 is shown in fig. 9 , both for r_o=0.04mm.

CONCLUSIONS

From the results presented in section-1, it is clear that downscaling of size of an optical system leads to the performance at the diffraction limit, where aberrations reduced significantly. OPD value shown in fig.1 (A)b is about 10 waves, while that of fig.1(C)b reduced to a value of 0.1 waves. Also, the Strehl ratio increases from a value of 0.014 in fig.1(A)d to a value of 0.97 in fig.1(C)d. However, the number of the resolved images are reduced according to the downscaling factor M. This recovered in the appearance of the letter F in fig.1e by multiplying the field size by 10 in fig.1(B), and by 100 in fig.1(C).

Considering the results presented in section-2 for single micro aperture microlens scanner for three cases studied, which are summarized in table-3, there is a compromise between the size of the system(total track of light), and resolution on the expense of the entrance pupil diameters ENPD that indicate the width of the light, and the wavelength used.

Comparing the results of $F_{\#}$ 5 and $F_{\#}$ 1.5 for the afocal telescopic micro scanner shown in fig.s 9-10. It is clear that the system with $F_{\#}$ 5 performs in diffraction limit. But the scanning angles (field of view) are much less than that of the system with $F_{\#}$ 1.5. However, the total track of the system in this case is shorter, which is a privilege for medical applications and the severe aberrations could be reduced a lot by incorporating aspherical sufaces for the designed lenses.

REFERENCES

[1] Jahns,J. and Karl-Heinz Brenner, “Microoptics from technology to applications,” Springer, 2004.

[2] Borrelli, N.F. Borrelli, “Microoptics technology,” 2nd.Edition, USA, 2005.

[3] Urey, N.Nestorovic, N.,… and A. Gross, “Optics Designs and System MTF for laser Scanning Displays,” Proc. SPIE 3689, 238-248, 1999

[4] H. Urey, "Retinal Scanning Displays," in Encyclopedia of Optical Engineering, R. Driggers, ed., (Marcel Dekker) pp.2445-2457, 2003.
[5] Software for Optical Design; Zemax Development Corporation, 2005.
[6] A.W. Lohmann, "Scaling laws for "lens systems," Applied Optics, vol. 28, no. 23, pp. 4996-4998,1989.
[7]M. Born and E. wolf," Principles of optics", Pergamonn press 1975.
[8] Chin-Pang-Billy Siu, Haishan Zeng, and Mu Chiao, "Magnetically actuated MEMS microlens scanner for in vivo medical imaging, "Optics Express, vol.15., no. 18, 2007.
[9] Steffen Glockner, Rolf Goring, and Torsten Possner, "Micro-Opto-Mechanical beam deflectors'', Opt. Eng., 36(5) 1339-1345, 1997.

Table (1) Data parameters of an aberrated thin lens.

$F_{\#}$ = 3.97	**Radius of curvatures R_1= 61.717mm, R_2= -316.615 mm**
Entrance Pupil Diameter ENPD = 25 mm	**λ= 0.486 µm**
Material glass BK7 , n=1.51	**f = 96.865 mm**
Conic =0 for all surfaces	**Thickness t = 4 mm**
Numerical aperture NA=0.125	**Total track = 100.86 mm**

Table (2) Data parameters of single aperture optical micro scanner, In all cases, scanning angles of microlens are 0^o,± 11.5^o, Conic k=0.361, R_1 = 1.31mm, R_2= infinity.

Cases	ENPD(mm)	λ(µm)	material	n	f(mm)	Track(mm)
1	0.3	1.064	PDMS	1.272	4.2	7.4
2	0.3	0.532	PDMS	1.4217	1.87	5.53
3	0.15	0.532	PDMS	1.4217	1.87	5.53

Table (3) Data parameters of Keplerain telescopic micro-scanner system with $F_{\#}5$.

ENPD with $F_{\#}5$	0.1mm
Radius of curvatures R_1=R_2=R_3	0.259mm
Focal lengths of lenses , $f_1 = f_2$	0.485 mm
Material glass Bk7 ,refractive index n	1.51
Thickness of lenses	t_1 =0.02mm, t_2=0.758
Conic for all surfaces k	0
Wavelength λ	0.532 µm
Numerical aperture NA (Image space)	0.099
Total track of system	2.46 mm

Table (4) Data parameters of Keplerian telescopic micro scanner with $F_{\#}$ 1.5.

ENPD with $F_{\#}$ 1.5	0.1 mm
Radius of curvatures , $R_1 = R_2 = R_3$	0.093mm
Wavelength λ	0.532µm
Thickness of lenses, t_1 and t_2	0.03mm, =0.27mm
Material glass Bk7 , n	1.51
Focal length , $f_1 = f_2$	0.148mm
Numerical aperture NA (Image space)	0.33
conic of all surfaces	0.0
Total track of light	0.99mm

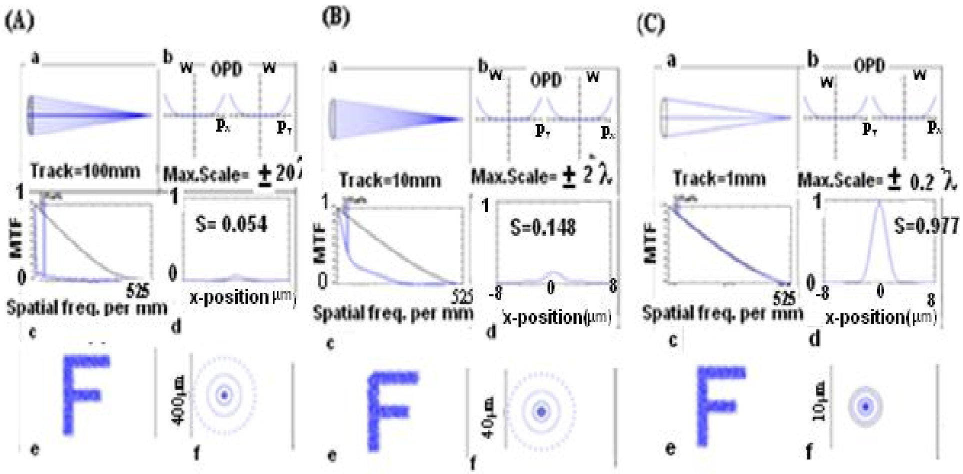


Figure (1) Characteristics of thin lens, (A) without scaling (macroscopic aberrated thin lens), (B) downscaling by 10, (C) downscaling by 100. Where a) layout, b) OPD, c) MTF, d) PSF, e) image formation of letter F , f) spot diagram.

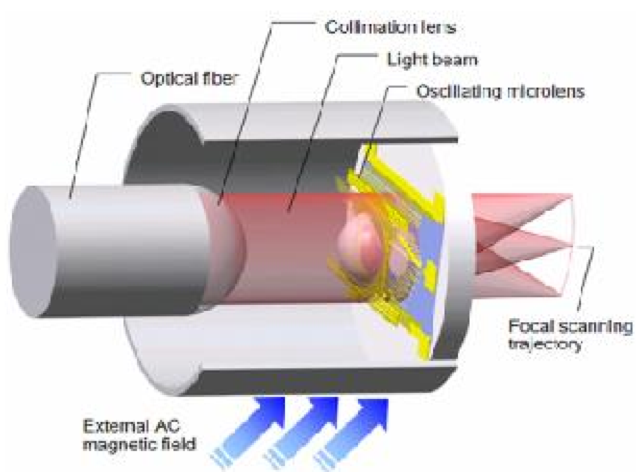


Figure (2) Schematic of single aperture micro scanner system[7].

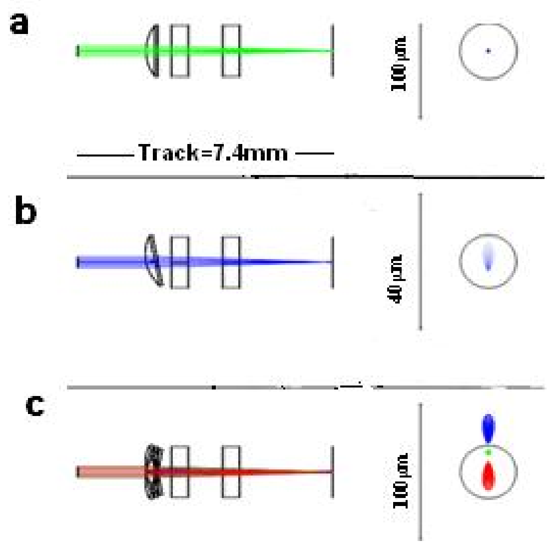
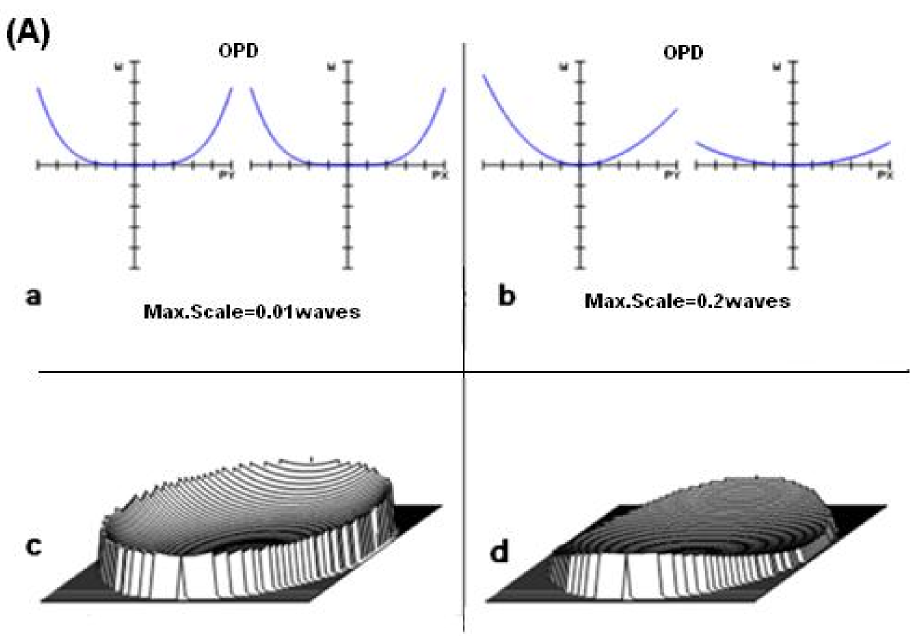


Figure (3) Layout of single aperture micro scanner(case 1, ENPD=0.3mm, λ = 1.064µm), a) at 0° tilt angle, b) at +11.5° tilt angle, c) at all tilt angles, on the right are shown spot diagrams at the image plane surrounded by the Airy disc .



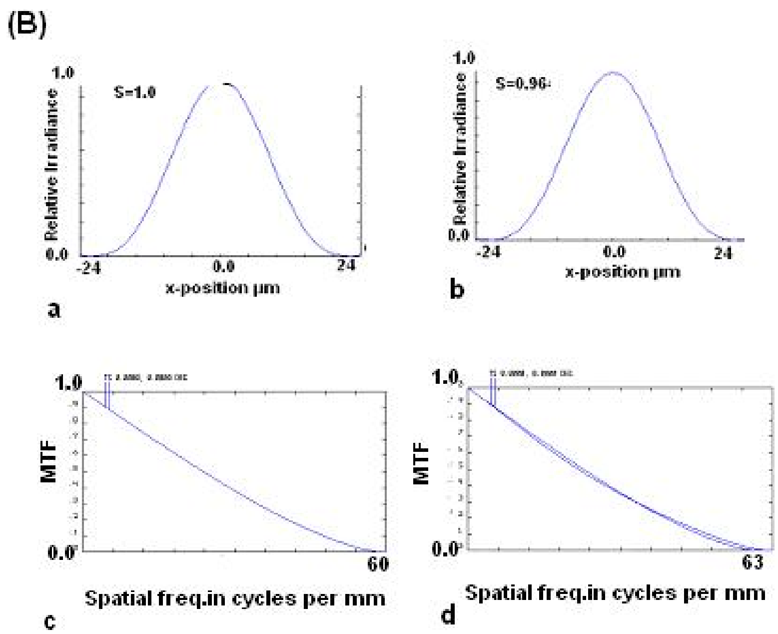


Figure (4) Characteristics curves of single aperture scanner (case 1, ENPD=0.3mm, λ=1.06 µm) (A)- a)OPD at 0^o tilt angle, b) OPD at +11.5^o tilt, c) wavefront map at 0^o tilt, d) wavefront map at +11.5^o tilt . (B) - a)PSF at 0^o tilt, b)PSF at +11.5^{o}tilt, c) MTF at 0^o,d) MTF at +11.5^o.

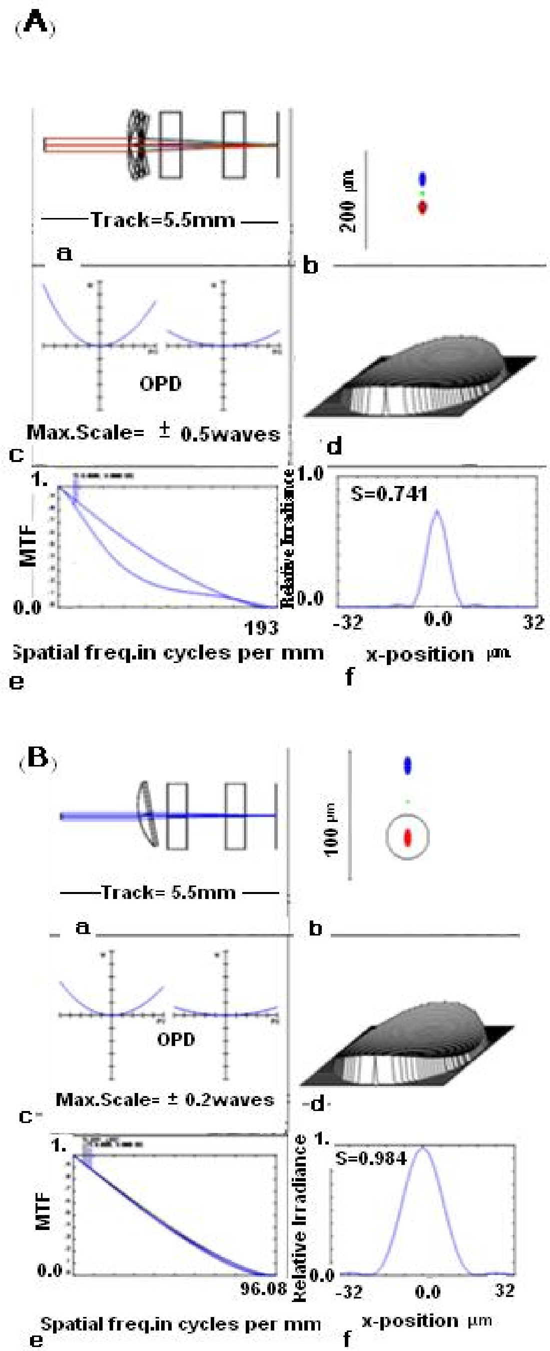
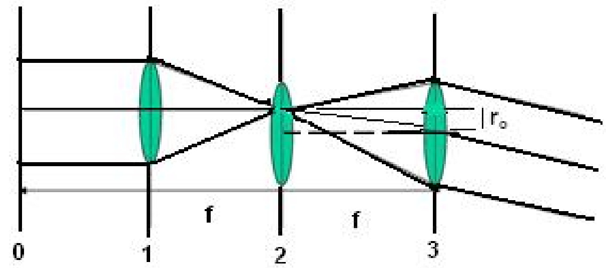


Figure (5) Characteristics curves of single aperture scanner, (A)(case 2, ENPD= 0.3mm, λ=0.53µm (B) (case 3, ENPD=0.15mm, λ=0.53µm) . For both - (a) Layout, (b) spot diagram, (c) OPD, (d) wavefront map, (e) MTF, (f) PSF with Strehl ratio S.



Figure(6) Keplerian Afocal telescopic type scanner system 1-objective lens, 2-field lens, 3- eyepiece lens [8].

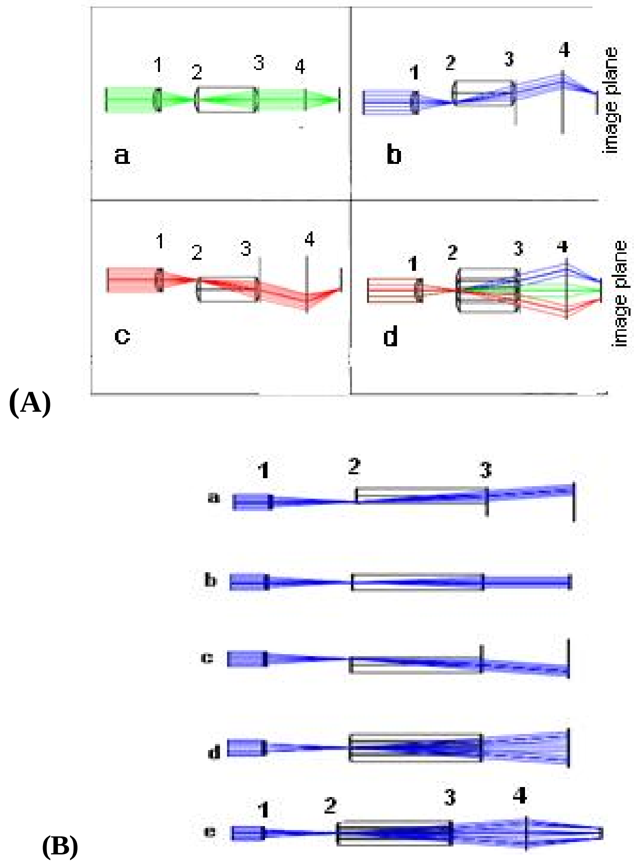


Figure (7) Designed Keplerian telescopic Afocal micro scanner system for maximum scan angle, (A) $F_{\#}$1.5, (B) $F_{\#}$ 5 [1focusing lens, 2 Mid lens and 3 last lens on the <u>same</u> substrate, 4 is an imaging lens] , where for both A & B a) r_o= + 0.04mm., b) r_o=0.0mm, c) r_o= - 0.04mm, d) at all scanning angles r_o= 0,±0.04mm, e) for B with imaging lens 4.

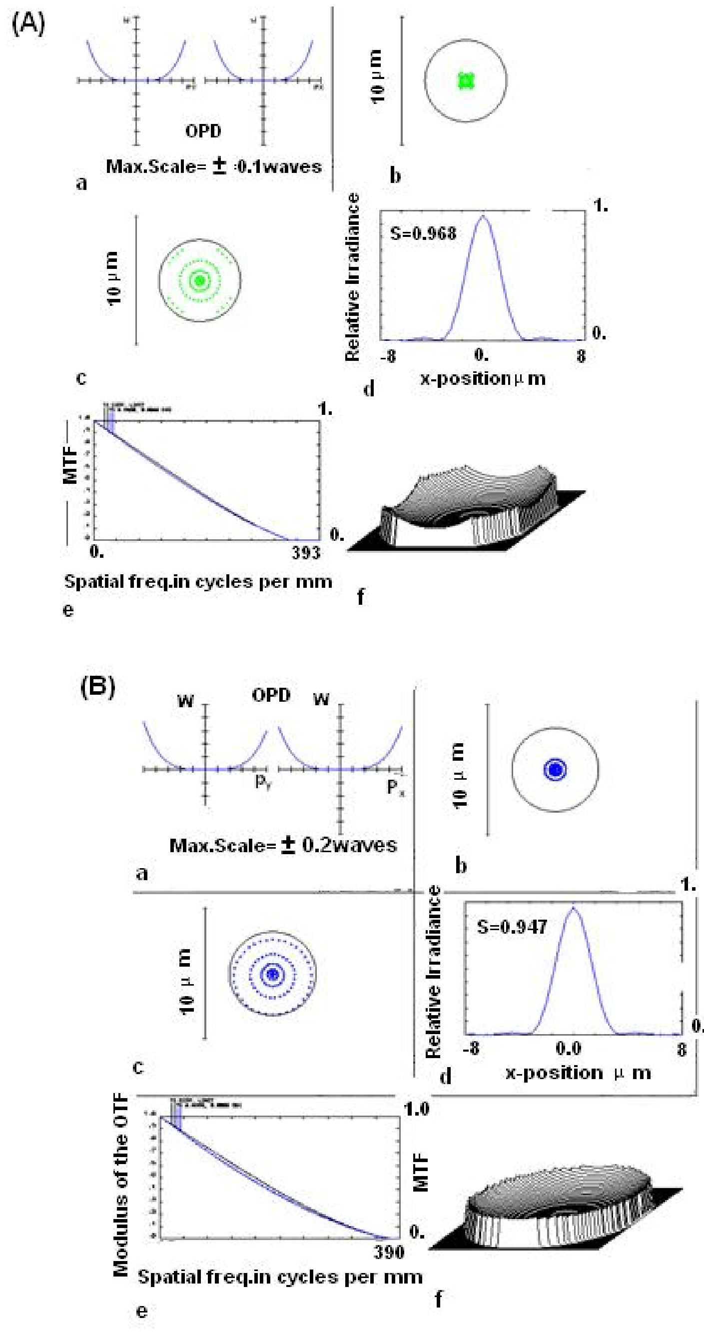


Figure (8) Characteristics curves of micro keplerian telescopic system with $F_{\#}5$, for (A) r_o=0.0mm (B)r_o=0.04mmm , where in both A & B a) OPD at image plane, b) spot diagram at mid focusing plane ,c) spot diagram at image plane, PSF with Strehl ratio S =0.968 in A & S=0.947 in B, e) MTF curve, f) wavefront map.

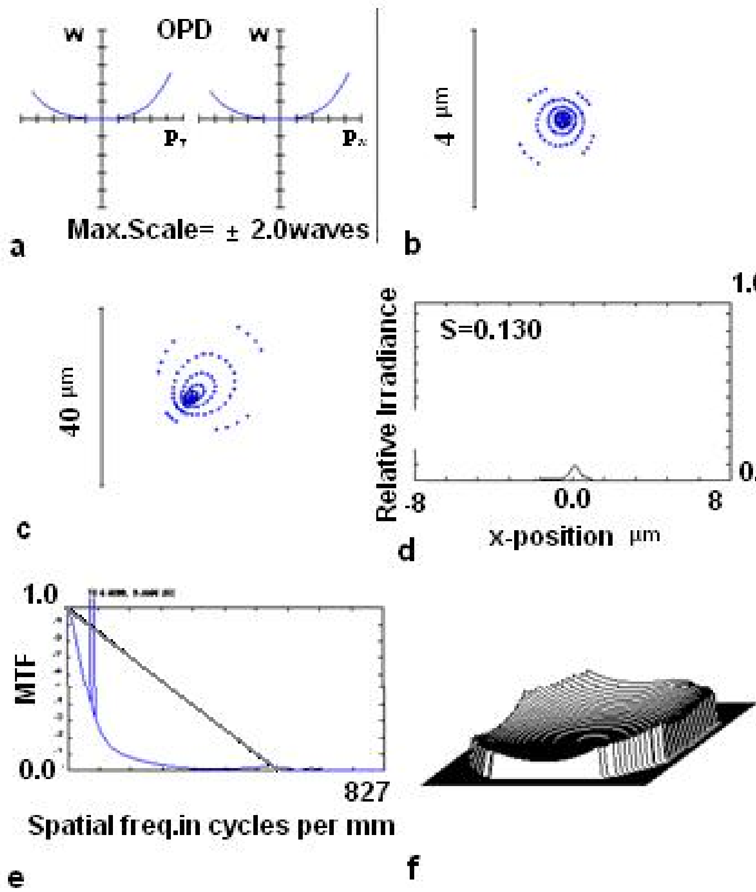


Figure (9) Characteristics curves of Keplerian micro telescopic system with $F_{\#}$ 1.5, for r_o=0.04mm , a) OPD at image plane, b) spot diagram at mid focusing plane ,c) spot diagram at image plane, d) PSF with Strehl ratio=0.130, e) MTF curve, f) wavefront map.