A COMPUTATIONAL INVESTIGATION OF LENS MATERIALS FOR PASSIVE INFRARED OPTICAL SYSTEM

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Abstract

A computational investigation has been adopted for designing an optical system for infrared homing head, operated in the region (3-5) µm. The design stage depends originally, on a standard optical system for IR homing head. These improvements include choosing the most suitable materials and features for each optical element in the developed design. An improvement stage was then followed for the correcting the radius of curvature of the correcting lens, which has process have been carried out using Zemax software to determining the most favorable optical properties i.e. spherical aberration, size of spot, and size and shape of the system. The results show that the best optical system was obtained when the dome and correcting lens are made of Sapphire material.

1- Introduction

Recent years have seen-a growth in the use and development of passive infrared sensors. These are desirable in two ways. First, the weapon delivery system can leave the immediate area or take cover when fired. Second, as the missiles home on radiation produced by virtue of the targets physical temperature, it is harder to decoy the missile or camouflage the target to prevent it radiating. All objects will emit some energy in the infrared bands depending on the type of target and temperature in the 3-5µm band will usually be used **[1]**.

A systems specification will initially define the total missile requirement. Such as nature of target, target aspect, and flight profile **[1]**.

A typical specification will include optical resolution, usually close to the diffraction limit, either in terms of Modulation Transfer Function “MTF”, the space volume for the optics, and the position of the focal plans and spot size **[1]**.

2-Theory

Two parameters have been taken into account to describe the efficiency of the optical system on image quality. These parameters are:

Spot size: All light rays intersect the optical axis at a single point, forming a spot with a size determined by the diffraction formula given by **[2]**:

$$\frac{d}{\lambda} = 1.22\,F\# \text{ .... } (1)$$

Where λ is the wavelength in meter, **d** is the diameter of the central maximum is in the same dimensions as the wavelength, and **F #** is the *F*-number defined as **[2]**:

$$F\# = \frac{f}{D}$$

where, **f** is the effective focal length of the system. D is the distance between aperture and the screen.

The size of the spot formed by an optical system can be calculated by **[3]**:

$$\text{Spotsize} = 2.44\lambda\,(F\#) + \frac{Tf}{(F\#)^3} \text{ ..... } (2)$$

where, **T** is a constant given by the following expression **[3]:**

$$T = \frac{n+2}{n(n-1)^2}B^2 - \frac{4(n+1)}{n(n-1)}B + \frac{3n+2}{n} + \frac{n^2}{(n-1)^2} \text{ ..}(3)$$

Where, **B** is the shape or bending variable, given by **[3]**:

$$B = \frac{r_2 + r_1}{r_2 - r_1} \text{ .... } (4)$$

N is the refractive index of the last surface, and r_1 and r_2 are the radii of the lens.

Second parameter is the Modulation transfer function **"MTF":** which is one of the most important parameter to determine the efficiency of the optical system in spatial frequency. MTF is very sensitive to many types of distortion, such as aberration. MTF represent the amount of image contrast relative to the object contrast **[4]**.

Seidel was formulated five sum expressions to calculate the primary aberration in terms of the data of the paraxial ray (u and h), and the optical invariance. The Seidel spherical aberration "S_I" is given by **[5]:**

$$S_I = -\sum_{\text{all surface}} A^2 h \Delta\left(\frac{u}{n}\right) \quad \text{.....................(5)}$$

Where, **h** is the high of object, u is the paraxial angle of incidence**, n** is the refractive index. The symbol **Δ** refers to the change of the quantities enclosed by the parentheses and **A** is defined as [5]:

$$A = nu + nhc \quad \text{..................................(6)}$$

Where c is curvature.

3- Infrared Optical System

The optical design of a homing head system used in infrared applications fields has been put forward with aid of ZEMAX program. Figure (1) shows the suggested optical design for infrared homing head system which is used in our work. The system consists of dome, primary mirror, secondary mirror, and correcting lens **[6].**

In our work, we select different materials that operate in the range (3-5) μm region of the spectrum.

The dome is meniscus lens, used to separate the received radiation on the face of the second element (primary mirror). The material of the dome is MgF_2, which have desirable optical properties.

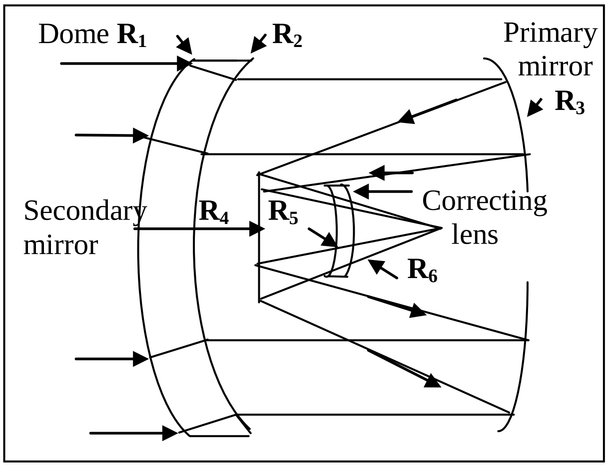

Figure (1) Optical system design of IR homing head [6]

The primary mirror is a concave one. The primary is used for receiving the radiation traversing the dome and delivers them to the surface of the third element (secondary mirror). Also, primary mirror is used to reduce the spherical aberration. The function of the optical system is highly affected by the distance between primary mirror and the dome. A high quality spot depends, on the distance between the dome and the primary mirror. However, there is a limitation to this distance. A short distance requires a high radius of curvature for the primary mirror to enable the rays to be collected on the surface of the secondary mirror.

The secondary mirror is a convex one. The secondary mirror is used to reflect the radiation coming from the concave mirror to be collimated by the fourth element (correction lens). The function of the secondary mirror is to bring back the radiation towards their original direction at a higher density and close to the optical axis. A small radius of curvature of the secondary mirror will increase the reflection angles of the rays which are collect in the vicinity of the secondary mirror that makes focusing on the detector rather difficult. However, a secondary mirror of large radius of curvature will make the rays to be collimated on the optical axis far from the mirror due to angles of reflection. This case would require that the secondary mirror should be followed by a correcting lens of a double convex type with large radii of curvature.

The double convex correcting lens is the fourth element in the homing head optical system. This lens has an important role in the focusing process. The radius of curvature of the correcting lens is desired such that the emerging rays are collimated vary close to the optical axis.

4. Numerical Results

Our computational work passes through two stages. **The first stage**: is an improving the optical system design. The improvement is done by changing the materials of the correcting lens and dome. With these materials, we get an additional characteristics related by its plentifulness and industrialization technique, and make the system more efficient. **The second stage**: is a descriptive investigation which utilizes to choose the optical parameters that describe the performance of the suggested optical system design.

Table (1) shows the abbreviation OBJ, STO, and IMA listed in **surface column** represent, the object, stop aperture, and image, respectively. It should be mentioned that in the IR lens, object indicate for IR rays coming from target, the stop aperture located in primary mirror, and the image represent the spot on the detector.

The radius, in **table (1)**, represents the radius of curvature of a lens. Infinity indicates for a plane surface i.e. a surface whose radius of curvature is infinity. The minus (-) and plus (+) signs indicate for a concave and convex surface, respectively for the lens under consideration.

Thickness, represent thickness of each optical element and separation between that element (air lens thickness).

Glass column contains the type of glass materials used in the lens design process. Semi diameters refer to the value of the lens aperture radius.

Standard design, define when the material of the dome is MgF_2 and the material of the correcting lens is Sapphire.

A trial and error method has been adopted in order to achieve the lowest possible spot size and the associated aberrations. The smallest size of spot requires solution of two important problems in order to achieve high resolution, the solution is as follows:

(i) Reducing spherical aberration to the lowest possible value which is the task of the correction.

(ii) Good focusing by the system elements which is the task of the collection part.

Table (1):
Optical data of standard design(All dimensions are in millimeter)

Surface	Radius	Thickness	Glass	Semi-Diameter
OBJ	Infinity	Infinity	air	0
1	40	4	MgF_2	17.5
2	32.77	32	air	16.941
STO	-84.5	-30	Mirro	17.953
4	-141	7.15	Mirro	6.447
5	46.88	1.8	Sapph	4.167
6	-115.8	8.97325	air	3.838
IMA	Infinity	zero	air	0.121

Table (2):
Data of the General lens

NUMBER OF SURFACES	8
Stop	4
Lens units	Millimeter
System aperture	Entrance pupil
Glass catalog	Schott Infrared
Effective focal length	45.32924
Back focal length	8.97325
Total track	36
F-number F/#	1.329849
Numerical aperture NA	0.3601563
Stop radius	17.97072
Entrance pupil diameter	35
Wavelength	3-5 μm
Field of view	0

The process are begins by varying R_5 and R_6, while the thickness of the correction lens is assumed to be constant. The method is repeated for different refractive index of the correcting lens material

The analytical consideration is to show what are the effective parameters that can provide a complete indication about how efficient the suggested optical system design. Since the function of the optical system design of an IR homing head is to detect and track a distance object, the accuracy of the calculations is very important. In order to achieve high accuracy, an analytical study on how to determine the effective parameters of the optical system has been performed. The analysis includes a test for some of well-known optical functions at different amounts of aberration and defocusing, then studying their behavior and how they are affected.

Figure (3) represent the MTF curve of the optical system for different materials that have been used in dome and correcting lens. This is as follows:

a- MgF_2 dome and Sapphire correcting lens

b- Sapphire dome and Sapphire correction lens

c- LiF dome and Sapphire correcting lens

d- BaF_2 dome and Ge correction lens

e- CaF_2 dome and Ge correction lens

f- NaCl dome and Ge correction lens

Table (3) shows the result of image quality after correcting the aberration. From the figure of spot we conclude that we get better spot since it have a high intensity with little diffraction pattern. Also, we approximately get a diffraction limit MTF curve after correction the aberration.

5.Conclusions

From our results we can conclude that:

The efficiency of the adopted system is depend on the radius of curvature for correcting lens. Also, In general, the best suggested suitable materials for IR homing head are Sapphire and Germanium material when used in correcting lens. While, another materials gives a high distortion in image. Furthermore, the best optical system was obtained when the dome and correcting lens are made of Sapphire material.

6.References

[1] Design Requirements for a Passive Infrared Homing Head Advance Infrared Detectors and System, pp 24-26 **[1983]**.

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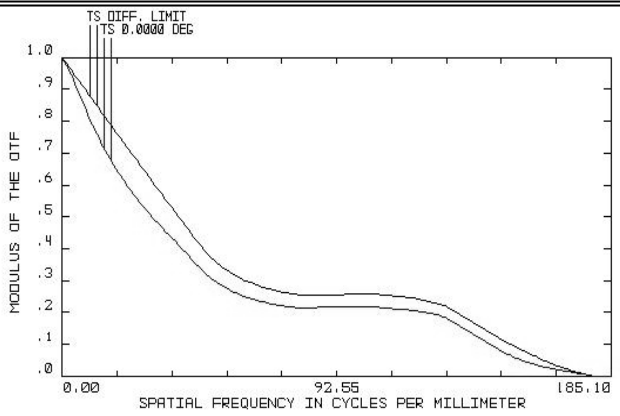
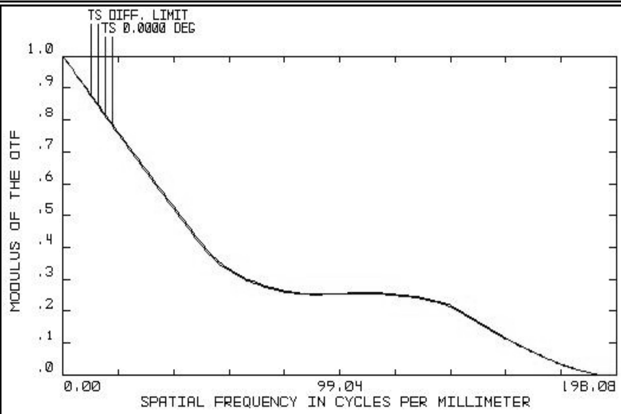
[5] Aberration of the Symmetrical Optical Systems Academic Press: London **[1974]**

[6] Optical Design for Infrared Missile Seeker, Proceeding of the IRE, June 30 **[1959]**, pp 1537-1539.



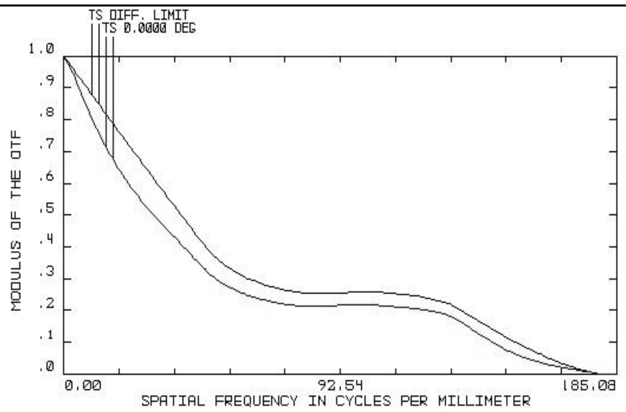
(a)

MTF for MgF_2 dome and Sapphire correcting lens



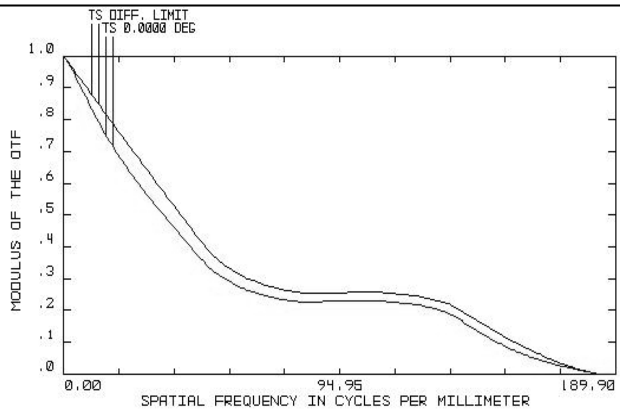
(b)

MTF for Sapphire dome and Sapphire correction lens



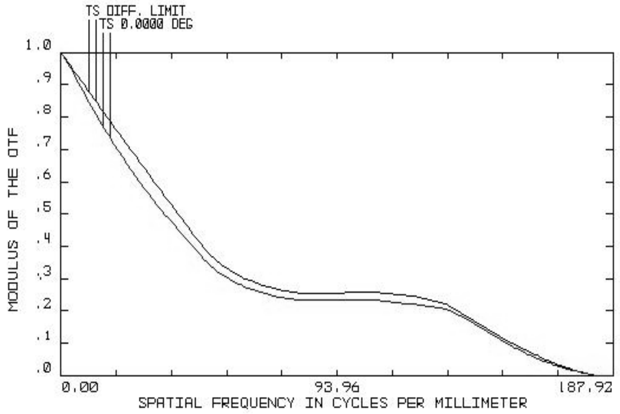
(c)

MTF for the LiF dome and Sapphire correcting lens



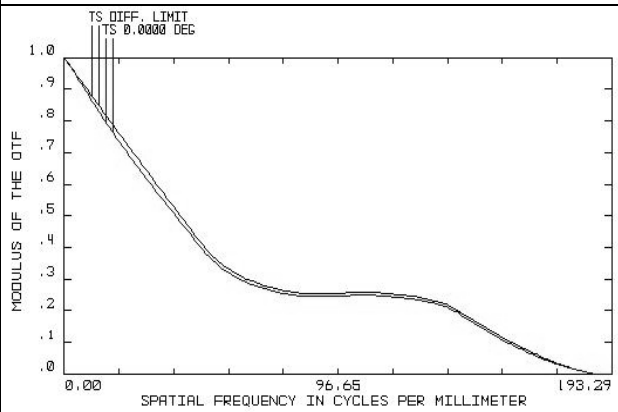
(d)

MTF for the BaF_2 dome and Ge correction lens



(e)

MTF for the for the CaF_2 dome and Ge correction lens



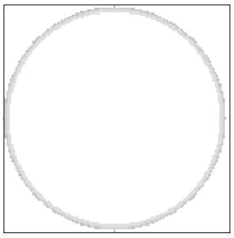
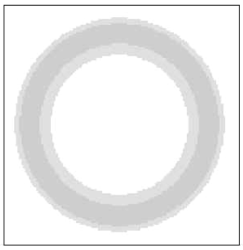
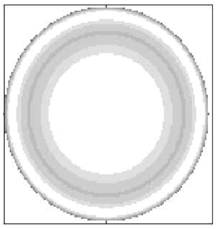
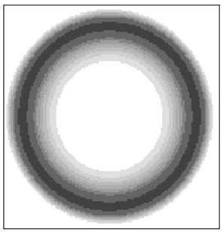
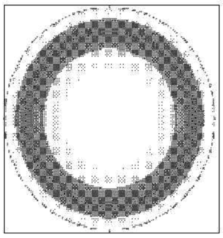
(f)

MTF for the NaCl dome and Ge correction lens

Figure (3)

The MTF of the optical system for different dome materials and different correcting lens materials with the corresponding diffraction limit

Table 3
The results for Domes materials, Correction lens materials, Spot size radius, Seidel spherical aberration (S_I), and the spot grey pattern

Dome materials	Correction lens materials	Spot size radius (μm)	Si	spot grey pattern
Sapphire (n=1.667)	Sapphire	40.363	0.00493	
NaCl (n= 1.5217)	Germanium	14.416	0.02402	
BaF_2 (n=1.455)	Germanium	34.789	0.02816	
CaF_2 (n=1.41)	Germanium	49.692	0.03645	
MgF_2 (n= 1.349)	Sapphire	43.143	0.03986	
LiF (n= 1.3494)	Sapphire	69.406	0.03956