Development of Multi-Channel IR Seekers Utilizing Binary Diffraction Optics

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ABSTRACT

New generations of infrared (IR) seekers adopt two or more detectors to define corresponding spectral lines of the target signature. An optical system composed of ordinary optical components (lenses and mirrors) are implemented to focus different incident spectral lines on the corresponding detectors. These ordinary optical components have diffraction losses of considerable amplitude which adds to their heavy weight, manufacturing complexity, and high production expenses. To overcome these drawbacks, a thin film Fresnel zone plate (FZP) lens is proposed to substitute the ordinary optical components in separating and focusing different spectral lines. The technology of FZP lenses is quite compatible with recent fabrication techniques.

In the present paper, a theoretical analysis and numerical calculations are given to verify the achievements of the proposed FZP in decreasing the diffraction losses, focusing the incident radiation, and enhancing the performance of the detector. The focusing and spectroscopic characteristics of the FZP are studied with varying the wavelength.

1- INTRODUCTION

The rapid growth and implementation of binary diffraction optics in both commercial and military systems have evolved to the stage of recent demonstrations and applications of the technology in miniature optical systems. In the same time, the technology of IR detectors has prompted novel and highly specialized IR seeker concepts. New generations of IR seekers adopt two or more detectors to define corresponding spectral lines of the target signature. The multi-channel IR seekers are mainly developed to overcome the problem of jamming by IR flares. The chromatic aberration of an ordinary optical telescope is being utilized to focus the incident radiation onto the detectors.

" Faster, better, cheeper " has provided new impetus for space guidance, control, and tracking components and subsystems to be smaller and capable of performing dual or multiple functions previously provided by additional and redundant hardware. In the

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present paper, a thin film Fresnel zone plate (FZP) lens is proposed to substitute the ordinary optical components in separating different spectral lines. In the same time, each spectral line is focused on the corresponding detector. Two configurations of the FZP lens-detectors system are proposed. Namely: the FZP lens is used to focus the incident radiation on: (1)two detectors positioned successively on the foci of the corresponding spectral lines, (2) multi-spectral line detectors composed of co-central rings of different materials sensitive to the corresponding spectral lines. In FZP lenses, the diffraction-limited focusing characteristics have been obtained[1]. In FZP lenses, the focalization is due to two phenomena:
(a) the diffraction effect which can be mathematically deduced from the Huygens-Fresnel principle, and
(b) the introduction in the diffraction plane of a correct phase shift or absorption distribution leading to constructive interference at the focal point.

The FZP lenses can be fabricated by an inexpensive planar microfabrication technique. The computer-drawn micro FZP lens is attractive[2] because it has several advantages:
(1) design flexibility; an arbitrary wave front is obtained by controlling its zone pattern,
(2) high reproducibility; it can be made by inexpensive lithographic technology, and
(3) light weight; the imaging part of the lens is only a few microns thick.

Using integrated optics techniques to draw the thin film FZP on the detector substrate will make the assembly rigid and perfectly focusing.

2- THE DESIGN OF THE FZP

The FZP is an aperture with alternating opaque and transparent circular regions that just coincide with the Fresnel zones appropriate to the values of the spectral focal length f and wavelength λ being used. The construction of the Fresnel zones is illustrated in Fig.1(a), where a plane wave of wavelength λ is incident perpendicular to the left side of a circular aperture and the spheres about the focal point F have radii differing by $\lambda/2$. The intersections of these spheres with the plane of the aperture form circular zones. Fig.1(b) shows the corresponding FZP.

The radius of the mth zone of the FZP is given by[3] :

$$r_m=\sqrt{mn\lambda f} \tag{1}$$

where n is the index of refraction at λ,
λ is the wavelength of the incident light,
f is the spectral focal length, and
m is an integer denoting the zone number.

Note that the area of any zone $\Delta\sigma$ is independent on m

$$\Delta\sigma=\pi(r^2_{m+1}-r^2_{m})=\pi n\lambda f=\pi r^2_1 \qquad (2)$$

The Fresnel zones are defined so that the phase difference δ changes by π across one zone and equals $m\pi$ at the edge of the mth zone, which is equivalent to changes in the path difference by $\lambda/2$ and $m\lambda/2$ respectively.

3- THEORETICAL EVALUATION OF THE FIELD AT THE FOCUS

Define the resultant amplitude of the light incident from the mth zone A_m, successive values of A_m will have alternating signs because changing the phase by π means reversing the direction of the amplitude factor. The total amplitude of the field at the focal point is given by

$$A=A_1-A_2+A_3-A_4+\dots\dots\dots+(-1)^{m-1}A_m \qquad (3)$$

$$A_m=C_1(1+\cos\theta) \qquad (4)$$

where θ is the angle at which the light leaves the zone, and C_1 is a constant independent on m.
Equation (3) can be reduced to

$$A=\frac{A_1}{2}+\frac{A_m}{2} \qquad m\dots odd \qquad (5)$$

$$A=\frac{A_1}{2}-\frac{A_m}{2} \qquad m\dots even \qquad (6)$$

as $m \rightarrow \infty$, θ approaches π for the last zone, and the oblicity factor causes $A_m \rightarrow 0$. The amplitude due to the whole wave is just half that due to the first zone acting alone[4]. Moreover, if the zone plate is composed of M zones, ½M zones are open, and is then opaque after that, then the field at the focal point is $M E_{na}$ and the focal flux density is

$$S = M^2 S_{na}$$

where S_{na} denotes the focal flux density for no aperture case.

4- FIELD DISTRIBUTION IN THE FOCAL PLANE (y=f)

An acceptable approximation of the 2-D zone plate shown in Fig.1(b), is proposed. In this approximation[5], the circular symmetry of the zone plate is utilized to simplify the mathematical calculations, and hence, the corresponding 1-D zone shown in Fig.2 will be considered. This 1-D zone plate is a set of pairs of identical slits representing the projection of the FZP.

Consider $x_M \ll f$ and $|x| \ll f$, which justifies many approximations.

The observed optical electric field at a point P_F due to a source at infinity and an aperture characterized by the transmission function $\tau(x)$, can be defined by Franhaufer diffraction formula as

$$E(x,f)=c'\int_{-\infty}^{\infty} E(\xi,0)\,\tau(\xi,0)\,\frac{e^{-ik\rho}}{\rho}\,d\xi \qquad (7)$$

where c' is a constant,
$k=2\pi/\lambda$, and

$$\rho=\sqrt{f^2+(\xi-x)^2} \qquad (8)$$

Since we assumed an incident plane wave, then the field amplitude at the aperture is independent on x.

$$E(x,f)=c'E(x,0)\int_{-\infty}^{\infty}\tau(\xi,0)\,\frac{e^{-ik\rho}}{\rho}\,d\xi \qquad (9)$$

The far field approximation for ρ is given by[6]

$$\rho \approx f - x\xi/f$$

and since the amplitude factor $1/\rho$ in Eq.(9) is less sensitive to small changes, then we can substitute $1/\rho \approx 1/f$. And Eq.(9) becomes

$$\begin{aligned} E(x,f) &= \frac{c'E(x,0)}{f}\,e^{-ikf}\int_{-\infty}^{\infty}\tau(\xi,0)\,e^{\frac{ik\xi x}{f}}\,d\xi \\ &= \frac{c'E(x,0)}{f}\,e^{-ikf}\;T(x) \end{aligned} \qquad (10)$$

where T(x) is defined by the integral in Eq.(10). The field amplitude may then be normalized, the relative amplitude at the focal line is given by

$$E(x) = \frac{T(x)}{T(0)} \qquad (11)$$

and the field intensity is given by

$$I(x) = |E(x)|^2 = \left|\frac{T(x)}{T(0)}\right|^2 \qquad (12)$$

So, we can evaluate the field at the focal line if we evaluate T(x).

To evaluate the effect of the 1-D zone plate shown in Fig.2, we apply Babinet's principle adding the separate effects due to each pair of slits. Consider the central zone (the 1st zone) to be open, its transmission function is defined by

$$\begin{aligned} \tau_1(x) &= 1\,, & |x| \le x_1 \\ &= 0\,, & \text{elsewhere} \end{aligned}$$

and its transform is defined by

$$T(x) = \int_{-x_1}^{x_1} e^{\frac{kx\xi}{f}} d\xi = 2x_1 \; sinc(\frac{kxx_1}{f}) \qquad (13)$$

The mth open zone is represented by a pair of slits characterized by the transmission function, shown in Fig.3, given by

$$\tau_m(x) = \tau_m(x-d_m/2) + \tau_m(x+d_m/2)$$

where τ_m is the box function of width ℓ_m ,

$$\tau_m(x) = 1 , \qquad |x| \leq \ell_m/2$$
$$= 0 , \qquad \text{elsewhere}$$

where $d_m = x_m + x_{m-1}$, and
$\ell_m = x_m - x_{m-1}$

The corresponding transform is

$$T_m(x) = 2\ell_m \; sinc(kx\ell_m/2f) \; cos(kxd_m/2f)$$
$$T_m(0) = 2\ell_m$$

The field amplitude at the focal line is, then, evaluated by

$$E(x) = \frac{T_1(x)}{T_1(0)} + \sum_{m=2}^{m=M/2} \frac{T_m(x)}{T_m(0)} \qquad (14)$$

where m denotes the mth open zone, and
M/2 is the total number of open zones.

The field intensity is given by

$$I(x) = |E(x)|^2 \qquad (15)$$

5- NUMERICAL RESULTS

Consider a dual channel IR seeker, with two IR detectors optimized to wavelengths λ_1=.8 μm and λ_2=2.5 μm. An FZP lens (1000 zones) is designed for an intermediate wavelength λ=1.5 μm with spectral focal length f=3mm. The FZP is made of fused quartz having indices of refraction n=1.45337, 1.4469, and 1.42991 at wavelengths λ=.8 μm, 1.5 μm, 2.5 μm respectively (the transmission of 10 mm thick plate of fused quartz is 93% at these wavelengths)[7].

The spectral focal lengths had been numerically evaluated as f_1=1.82 mm and f_2=5.59 mm corresponding to λ_1=.8 μm and λ_2=2.5 μm respectively. This means that the corresponding detectors should be placed at axial distances, from the FZP, equal to f_1 and f_2 respectively.

The relative field amplitude distribution E(x,y) and the relative field intensity distribution I(x,,y) had been evaluated as a function of the axial distance Y and the transverse distance X. The plots of E(x,y) and I(x,y) are shown in Fig.4 and Fig. 5 respectively. The plots show clearly the focusing and spectroscopic characteristics of the FZP lens.

6- CONCLUSION

A diffraction limited FZP lens is proposed to separate and focus different spectral lines of the incident radiation onto the sensitive area of the corresponding IR detectors. The FZP lens is easy to implement utilizing inexpensive thin film coating and modern integrated optics techniques. The proposed thin film FZP lens substitutes the ordinary optical components used for the same application, and the FZP lenses present non of the drawbacks of the double refractive surfaces lenses.

A theoretical analysis is presented for the proposed FZP. Approximate formulas are derived for the field amplitude and intensity distributions. The field amplitude and the intensity are evaluated for a FZP to work with the IR detectors. The results of the analysis and numerical evaluation of the proposed case are satisfactory. The focusing and spectroscopic charactersitics of the proposed FZP are presented.

7- REFERENCES

1- T. Suhara, K. Kobayashi, H. Nishihara, and J. Koyama, "Graded-index Fresnel lenses for integrated optics", Applied Optics, VOL. 21, NO. 11, pp. 1966-1971, June 1982.

2- K. Tatsumi, T. Saheki, and K. Nukui, "High-performance lens fabricated by UV lithography", Applied Optics, VOL. 23, NO. 11, pp. 1742-1744, June 1984.

3- M. B. EL Mashade and A. Abdel Galil, "A theoretical analysis of a new confocal integrated optics semiconductor laser", Proceedings of the 9th National Radio Science Conference, Cairo, Egypt, pp. 1D9-8D9, 1992.

4- Francis A. Jenkins and Harry E. White, Fundamentals of Optics, Fourth Edition, Ch. 9, Mc Graw-Hill International Book Company, Tokyo, 1981.

5- Magdy Z. Mohamed and A. Abdel Galil, "Enhancing performance of IR detectors utilizing modern integrated optics techniques", Proceedings SPIE Infrared Detectors and Focal Plane Arrays III, Vol. 2225, pp. 384-392, 1994.

6- Miles V. Klein and Thomas E. Fortak, Optics, 2nd Edition, Ch. 7, John Wiley&Sons, New York, 1986.

7- Warren J. Smith, Modern Optical Engineering, The Design of Optical Systems, Second Edition, p. 174 Mc Graw-Hill Inc.,New York,1990.

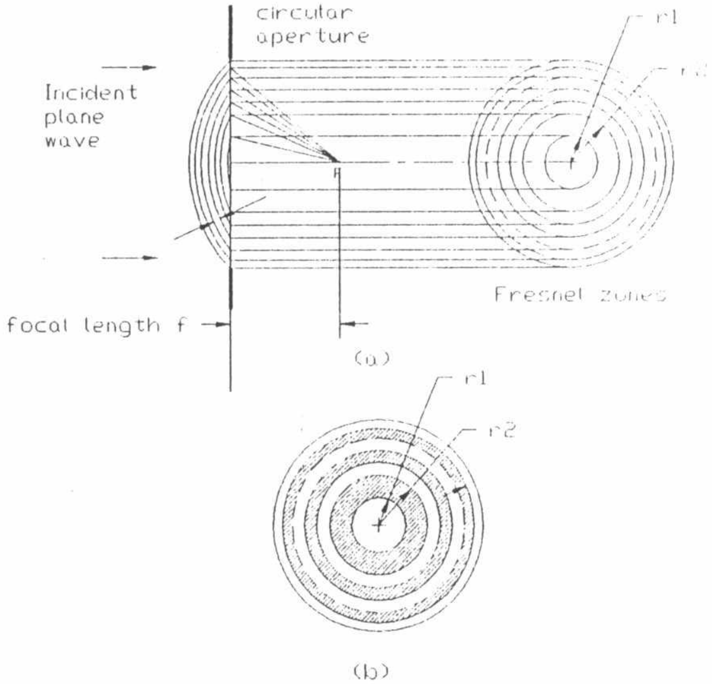

Fig.1 (a) Construction of the Fresnel zones.
(b) The corresponding FZP.

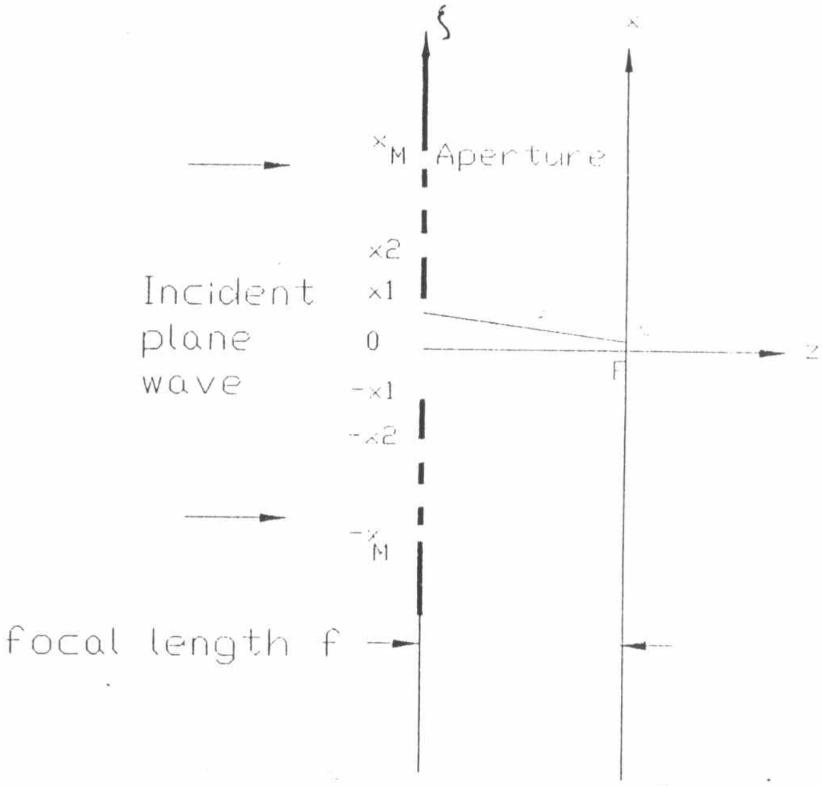

Fig.2 The 1-D zone plate corresponding to
the 2-D FZP of Fig.2(b).

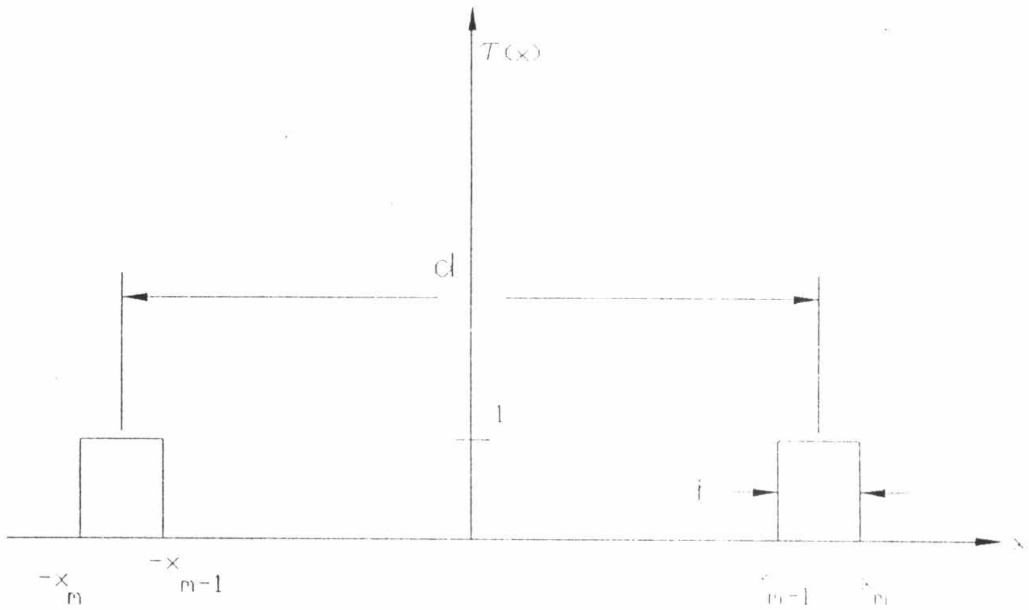

Fig.3 The transmission function for an identical pair of slits.

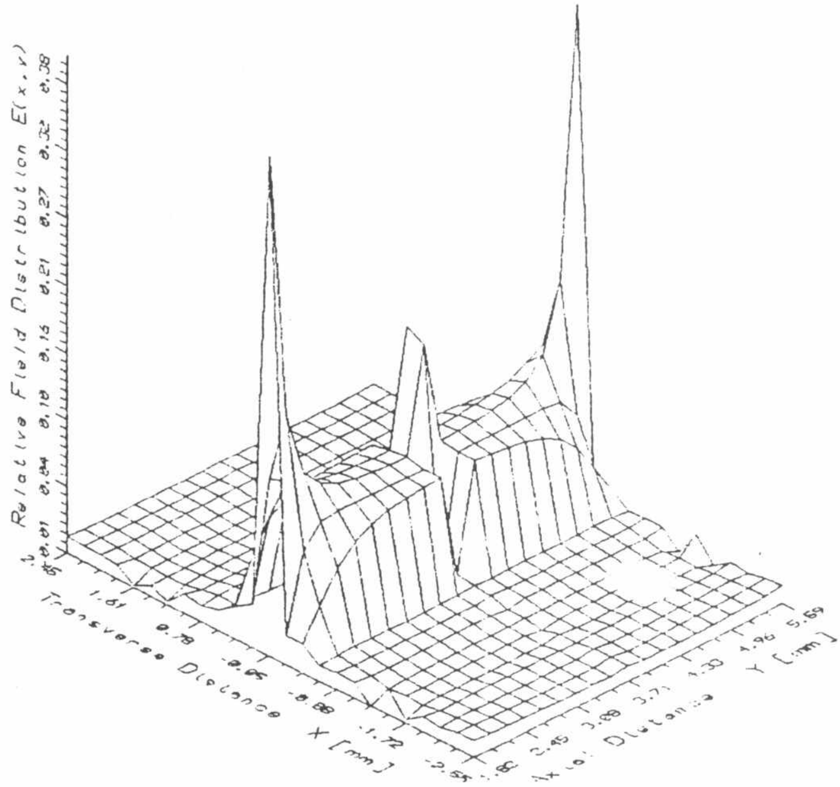

Fig.4 The relative field amplitude distribution of the 1-D zone plate of Fig.2

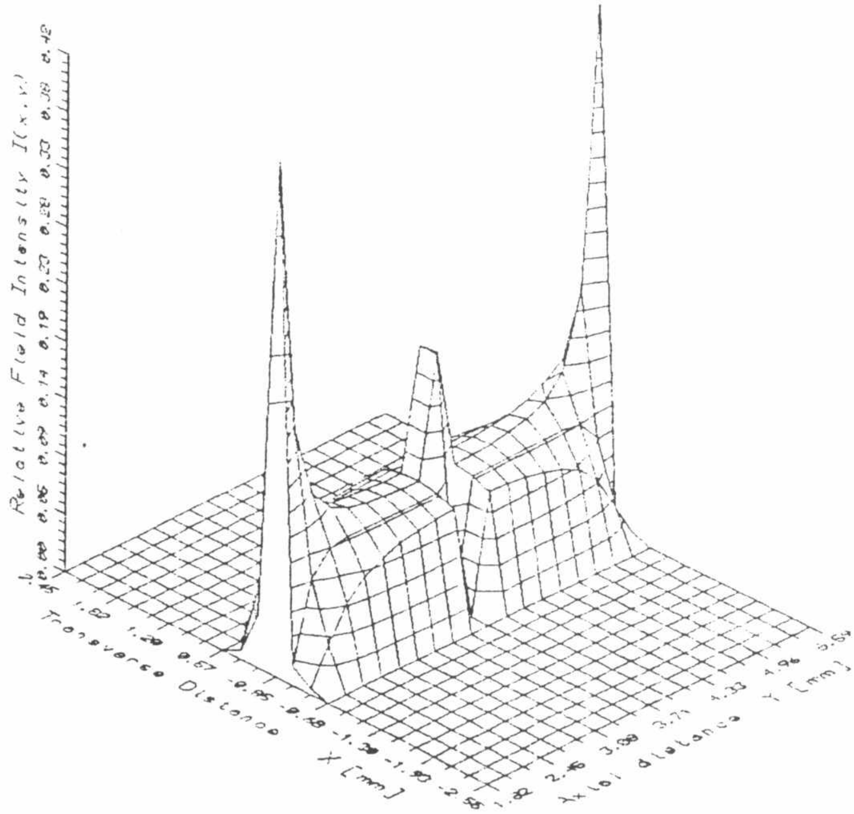

Fig.5 The relative field intensity distribution of the 1-D zone plate of Fig.2