Fresnel lens array with spatial filtering for passive infrared motion sensor applications

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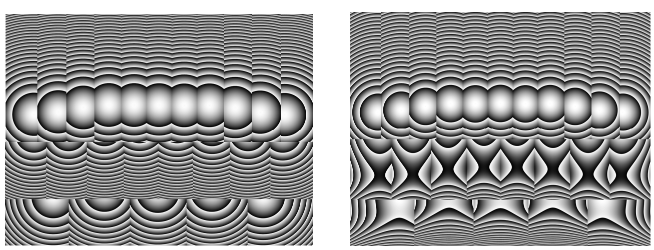
Abstract

In this work a Fresnel lens array for Passive InfraRed (PIR) motion sensors was designed, fabricated and tested. The resulting spatial filtering lens array presents the capability of distinguishing the presence of humans from small pets. Such array - designed to operate in the visible range of the spectrum - was manufactured on a Diamond-Like Carbon (DLC) thin film, using well-known microfabrication process steps. The optical testing was performed with an incoherent white light source. The fabricated lens was used to image an intensity input object onto a CCD array camera. The obtained results demonstrate that the optical power detected is attenuated for targets with inherently horizontal mass distribution (e.g. pets) while the optical power is enhanced for targets with vertical mass distribution (e.g. humans).

Introduction

PIR motion sensors has been extensively used in domestic and corporative electronic security applications. Its principle of operation is based on pyroelectric detectors – a PZT ceramic-based device which is responsible for transducing the incident IR radiation into electric signal. Associated with the photo detector and conditioning circuitry [1], there is a multi zonal Fresnel lens array, which monitors different spatial zones and collects the IR radiation from a body that moves inside the monitoring volume. The lenses are designed to concentrate as much IR radiation as possible onto the detector´s surface. The electrical current in the in the pyroelectric detector is proportional to the rate of change in time of the temperature of the target. The electrical waveform at the pyroelectric detector output depends on the distance between the detector and the target mass, on the amount of mass present in the target, and on the speed of the target with respect to the sensor. The sensor operates in the range of 8-14 micrometers wavelength. Whenever electrical signal is present at the output of the pyroelectric detector, meaning that an intruder has been detected, the sensor will trip. Figure 1 shows the photography of the phase distribution, mapped in grayscale, of a Fresnel lens typically employed in IR motion sensor applications. Figure 1a shows an image of the phase distribution of a conventional lens array, and figure 1b shows the phase distribution of the proposed Fresnel lens array with spatial filtering.



(a) **(b)**

Figure 1: Photography of a multi-zonal, segmented Fresnel lens typically used in PIR sensors. (a) grayscale image of the phase distribution of a conventional segmented Fresnel lens array, (b) grayscale image of the phase distribution of the proposed Fresnel lens array with spatial filtering.

Several companies have been employing various techniques in order to give the sensor the ability of distinguish human targets from pet targets. They are based on the use of microcontrollers, to execute a digital post-processing of the electric signal generated by the pyroelectric transducer, i.e., the signal is collected and then processed (filtered) [2]. A low-cost solution, however, can be obtained by employing optical filtering. The phase distribution of the Fresnel lens array of the sensor can be modified in order to accomplish the distinction between the presence of humans and pets through optical processing. To solve the pet immunity problem in PIR motion sensors, an approach that consists of a hybrid optical pre-processing/digital post-processing, also called wavefront coding [3-5], can be applied. Authors have reported the successfull employment of wavefront coding to correct the aberrations present in incoherent image systems [6,7], making them invariant to misfocus within a predefined range of image plane distances as well as correcting the transversal chromatic aberration [8]. Because of the aberration invariance, it is possible to use low-cost and low-precision optics to produce a system with a performance similar to those using high-cost and high precision optics, or near diffraction-limited optical systems. In this paper we verify the application of the cubic phase distribution to improve the immunity of PIR sensors to false alarms generated by domestic pets. More details about the design and application of wavefront coding can be found on a previous work [9,10].

Application of the proposed Fresnel lens array on PIR motion sensors

Regular Fresnel lenses used in PIR motion sensors do not distinguish the presence of humans from pets. In order to accomplish this distinction using a low-cost solution, the phase distribution of the proposed lens is superimposed on the regular quadratic phase distribution lens (figure 1b). In our application, the new lenses are used as a spatial filter rather than as an imaging system. The filter was applied in one-dimension (in the vertical direction), and might be located at the exit pupil of the optical system (just behind the conventional quadratic distribution lens). Its phase function has the form shown in equation 1, where P_v is the generalized exit pupil function, located in the (x_p, y_p) exit plane [3].

$$P_V(x_p, y_p) = \exp\left[j20\pi y_p^{\ 3} \right] \tag{1}$$

Figure 2 shows the results of a numerical simulation. Figure 2a shows the intensity distribution of an input image containing typical, scale-respect, a human and a small pet silhouettes. Figure 2b shows the respective intensity distribution of the output image obtained from the input distribution of figure 2a, after processed by the resulting lens (figure 1b). One can note from figure 2b that the image of the human body has higher brightness when compared with the image of the small pet. Therefore, the lens of figure 1b makes possible to distinguish the presence of humans from pets, based only on optical filtering.

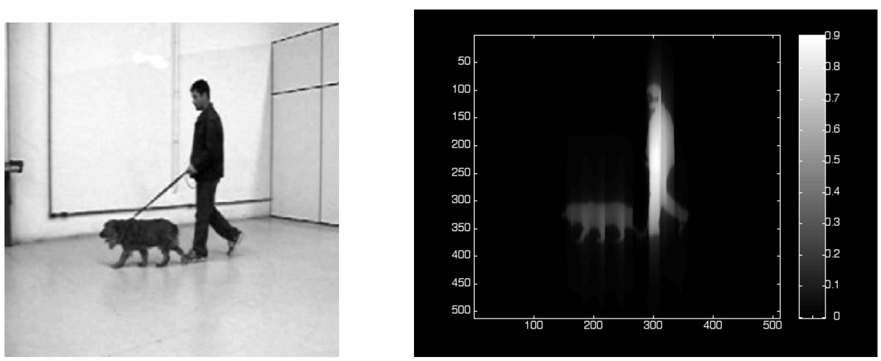
(a)  (b)

Figure 2: Numerical results. (a) Intensity distribution of an input image containing typical, scale-respect, human and a small pet silhouettes; (b) intensity distribution of the respective image obtained from the input distribution of figure 2a, after processed by the resulting cubic-phase distribution of the lens (figure 1b).

Manufacturing process of proposed Fresnel lenses

In order to show how the lens can be employed in the distinction of human targets from pet targets, we designed and manufactured a lens set on DLC thin film by microfabrication process techniques [11, 12], such as plasma-assisted deposition, microlithography and plasma etching. Although the sensor operates at the 8-14 micrometers wavelength range, we fabricated a diffractive Fresnel lens which operates in the visible portion of the spectrum, with a central wavelength of 500 nm. This is a suitable way to show that the principle works, being directly applied in the desired wavelength range (mid infra-red). For comparative purposes, besides each cubic-phase distribution Fresnel lens, we fabricated also a conventional Fresnel lens. Both lenses were submitted at the same process steps during the whole fabrication process. The continuous phase distribution shown on figure 1b might be implemented through a micro-relief on the 1.5 mm-thick DLC layer, using the following relation (equation 2), where $th(x_p,, y_p)$ is the thickness variation within the transparent carbon film, λ is the operating wavelength, n_{DLC} is the refractive index of the DLC layer (measured at wavelength λ) and $\phi(x_p,y_p)$ is the phase distribution information $[0 \le \phi(xp,yp) \le 2\pi]$ [13].

$$th(x_P, y_P) = \frac{\lambda}{2\pi(n_{DLC} - 1)} \phi(x_P, y_P) \qquad (2)$$

Based on a previous work [10, 14] the process which was adopted for deposition of the films, has a deposition rate of approximately 16 nm/min. Varying the processing time up to 90 minutes yielded films with different thicknesses up to 1500 nm. The deposition rate proved to be constant in time [15]. The refractive index of the film, n_{DLC}, as deposited onto a silicon wafer and measured by ellipsometry technique, is 1.60 at the 633 nm wavelength. A DLC film of 2 μm thick absorbs approximately 6% of the incoming light ($400 < \lambda < 700$ nm), as measured by the UV-Vis-NIR spectrometric technique [16,17]. In order to fabricate diffractive structures with 8 phase levels, it is necessary to perform three lithographic steps followed by plasma etching sequences: the first one which removes 104 nm (π/4 phase modulation), the second one which removes 208 nm (2π/4phase modulation) and the third one which removes 416 nm (4π/4 phase modulation). In this way, the maximum thickness of removed film is 728 nm (7π/4 phase modulation). A photography of a wafer with the fabricated diffractive lenses is shown in figure 3a. More details about the micromachining process steps for lens fabrication can be found on previous works [10,14].

Optical results

Figure 3b shows the experimental set up employed to perform the comparative tests. The object, located in the back focal plane of the lens, is illuminated by a diffused incoherent white light source. The lens produces the image the object directly in the plane of the CCD camera.

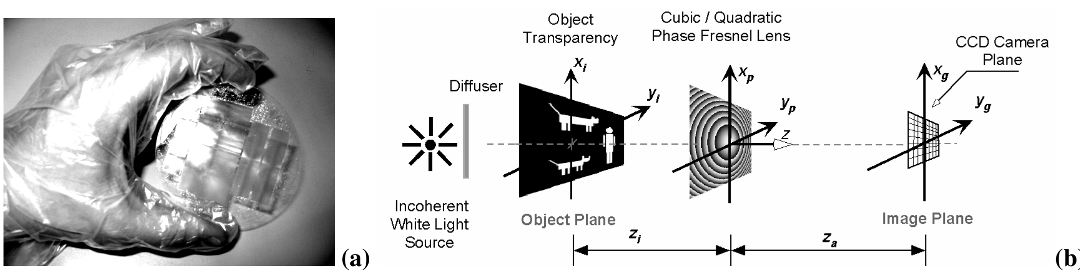


Figure 3: (a) Photography of a 3-inch diameter glass wafer with both the proposed (cubic phase) and conventional (quadratic phase) lenses; (b) experimental set up employed to store the images produced by the fabricated Fresnel lenses. The object plane is illuminated by a diffused incoherent white light source and the lens images the object directly in the CCD plane of the camera.

Figure 4 shows the resulting images formed by the fabricated Fresnel lenses. Figure 4a and 4b show the resulting images from the conventional lens (quadratic phase profile) and the proposed lens (cubic phase profile), respectively. One can see that cubic phase profile spreads the light as predicted by the simulated results. The optical power generated by pet targets is attenuated (to a value of about 50% of the maximum value), as compared with human targets. Therefore we showed that wavefront coding approach can be used to allow some blurring of the PSF of the optical system in such a way that it turns possible the discrimination between humans and pets for passive infra-red motion sensor applications.

Conclusions

In this work we described the wavefront coding method applied to passive infrared motion sensors. The new proposed lens has the ability to distinguish the presence of humans from pets. The lenses are designed considering a cubic phase distribution placed in the exit pupil plane of the sensor. We verified the behavior of the cubic phase mask in one-dimensional systems, testing this distribution in the vertical as well as horizontal directions. We simulated several qualitative human bodies in different conditions, and small pets. Through the fabrication of conventional quadratic phase profile and proposed cubic phase profile lenses, we demonstrate that the proposed system is able to enhance the information of the vertical features, turning possible, in this way, the distinction of the presence of humans from pets. The novelty of this work is the fact that the so-called pet immunity function was implemented in a purely optical filter. As a result, this approach allows one to reduce some hardware parts as well as decrease the software complexity once the information about the intruder transduced by the pyroelectric sensor has already been optically processed.

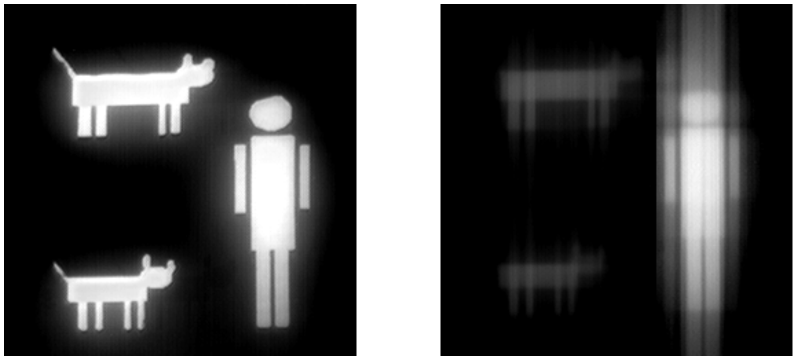


Figure 4: Resulting intensity images generated from the Fresnel lenses in the visible range of spectrum. (a) resulting image from the conventional (quadratic phase profile) lens; (b) resulting image from the proposed lens (cubic phase profile). One can note the enhancement of the human body intensity distribution

Acknowledgements

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References

[1] US patents: 4,052,616 (1977), 4,321,594 (1982), 4,535,240 (1985).
[2] US patents: 5,473,311 (1995), 5,670,943 (1997), 5,870,022 (1999), 6,188,318 B1 (2001).
[3] Edward R. Dowski, Jr., and W. Thomas Cathey "Extended depth of field through wave-front coding" Applied Optics, **34 (11)**, 1859-1866 (1995).
[4] Dowski, E. R. Jr. and Johnson, G. "Marrying optics & electronics: Aspheric optical components improve depth of field for imaging systems", Optical Engineering Magazine, **2** (**1**), 42-43 (2002).
[5] US patents: 5.748.371 (1998), 6.069.738 (2000).
[6] Dowski, E. R. Jr.; Cathey, W.T.; van der Gracht, J. "Aberration Invariant Optical/Digital Incoherent optical Systems", Publication of the Imaging System Laboratory Department of Electrical Engineering, University of Colorado, Boulder, available (07/18/02) at: http://www.colorado.edu/isl/papers/aberrinv.pdf
[7] Cathey, W. T.; Dowski, E. R.; and Alan R. FitzGerrell, A. R. "Optical/Digital Aberration Control in Incoherent Optical Systems" Publication of the Imaging System Laboratory, Department of Electrical Engineering, University of Colorado, Boulder, available (07/18/02) at: http://www.colorado.edu/isl/papers/aberration/paper.html
[8] Wach, H.B., Cathey, W. T.and Dowski, E. R "Control of Chromatic Focal Shift Through Wavefront Coding" Publication of the Imaging System Laboratory Department of Electrical Engineering, University of Colorado, Boulder, available (07/18/02) at: http://www.colorado.edu/isl/papers/chromaberr.pdf
[9] Cirino, G.A.; Neto, L.G. "Design of cubic distribution lenses for passive infrared motion sensors", *Thermosense XXV*, Orlando, editors: K.E. Cramer & X.P. Maldague, Proceedings of the SPIE vol. 5073, pp.476-484, SPIE, Orlando-FL (2003).
[10] Cirino, G.A.; Neto, L.G. "Optical implementation of cubic-phase distribution lenses for passive infra-red motion sensors", *Thermosense XXVI*, Orlando, editors: Burleigh, D.B., Cramer, K.E. & Peacock, G.R., Proceedings of the SPIE vol. 5405, pp.189-198, SPIE, Orlando-FL (2004).
[11] Campbell, S.A., *The Science and Engineering of Microelectronic Fabrication*, Oxford University Press: Oxford and New York, pp. 252-275, 1996.
[12] "Amorhous Hydrogened Carbon Film", International Application - Patent Cooperation Treaty, nr. PCT/BR 02/00067 (2002).
[13] O´Shea, D.C., Suleski, T.J., Kathman, A.D. & Prather, D.W., *Diffractive Optics: Design, Fabrication and Test*, SPIE Press: Washington, pp. 115-121, 2004.
[14] L.G. Neto, P.S.P. Cardona, G.A. Cirino, R.D. Mansano, P. Verdonck; "Design, fabrication, and characterization of a full complex-amplitude modulation diffractive optical element"; J. Microlithography, Microfabrication and Microsystems, **2 (2)**, pp. 96-104, (2003).
[15] R. D. Mansano, M. Massi, L. S. Zambon, P. Verdonck, P. M. Nogueira, H. S. Maciel, and C. Otani, ''Effects of the methane content on the characteristics of diamond-like carbon films produced by sputtering'' Thin Solid Films **373**, pp. 243–246 (2000).
[16] J.C. Manifacier, J. Gasiot, J.P.Fillard, "A simple method for the determination of optical constants n, k and the thickness of a weakly absorbing thin film", J. of Physics E (**9**), pp.1002-1004 (1975).
[17] L.D. Caro, M.C. Ferrara, "Simple method for the determination of optical parameters of inhomogeneous thin films", Thin Solid Films **342**, pp.153- 159 (1999).