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CONCEPTION OF A CHEAP INFRARED CAMERA USING PLANAR OPTICS

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ABSTRACT:

Huge efforts are made in the research and industrial areas to design miniaturized and low cost infrared optical systems. Indeed these new breakthroughs will contribute to spread these systems in new outlets. Our purpose is to design a cheap micro-imager using only one lens with minimum price of manufacturing process. The use of planar optics could be an interesting challenge to reduce the price of fabrication of the camera. They need few matters and moreover they can be made with cheap unconventional materials. In this paper, we present a new concept of a compact uncooled infrared camera composed of a single planar Fresnel lens. Up to now, Fresnel lenses have not been yet used in the broadband imagery domain because of their chromatic properties. However we will show how we can limit the unwanted effects of the Fresnel lens. A prototype has been made for low-cost surveillance applications and experimental images are presented.

1. INTRODUCTION

In the uncooled infrared domain, industrials are interested in producing cheap infrared microcameras for low-cost applications. Important progress has been made in recent years in designing low-cost uncooled detectors that produce clear images [1,2]. To reduce the cost of the detector, sensor manufacturers have proposed to reduce the global size of the microbolometer array. ULIS has recently launched a very small detector composed of only 80x80 pixels with 34 μ m pixel pitch for low cost applications. However, the problem when we want to design a very inexpensive imager remains that the optical elements that are traditionally used to design the camera are too expensive. Infrared optical elements are generally made with expensive materials like germanium and the challenge for the optical designer is to explore new designs using cheap materials such as silicon, chalcogenide glasses or polyethylene that can be massively replicated by molding process or photolithography. Silicon and polyethylene are not commonly used because they are absorbing. The use of a planar

optics such as a Fresnel lens could minimize the effects of absorption. If we design a camera that is based on a single thin Fresnel lens we expect to cut costs significantly.

2. THE FIRST ORDER FRESNEL LENS

The Fresnel lens is an old concept dating from the eighteenth century. The idea to create a thinner and lighter lens is from Buffon in 1748. Buffon's work was followed by that of Fresnel who manufactured the first Fresnel lens in 1822 for lighthouses. Metallic parabolic reflectors that were initially used in lighthouses were too absorbing due to their poor reflectivity, so the idea was to replace them by a lens. The large diameter of the optics that was needed to enable maximum light capture prevented from using a classical lens which would have been too heavy and bulky. In that context, Fresnel proposed to replace reflectors by a Fresnel lens which is much thinner and lighter than a classical lens.

A Fresnel lens is a lens made of prismatic sections of circular fashion. Traditionally, when a ray goes through a lens it delays the incident wave a quantity proportional to the thickness of material crossed. The complex amplitude of the output wave is then proportional to a complex exponential of the phase which is itself proportional to the thickness of the lens. A phase jump of multiples of 2π has no effect on the complex amplitude of the output wave. The principle of the first order Fresnel lens will be to cut the lens every time the phase it introduces is equal to 2π at a given wavelength λ_0 which is called the blazed wavelength. A 2π phase jump at λ_0 is equivalent to a reduction of the thickness of the lens of a fixed quantity e .

At a given discontinuity and at the blazed wavelength λ_0 , the following relationship must be verified:

$$\phi = 2\pi \frac{(n-1)e}{\lambda_0} = 2\pi \quad (1)$$

So the thickness of material at a discontinuity (e), or the groove depth, is given by:

$$e = \frac{\lambda_0}{(n-1)} \quad (2)$$

Thus a first order Fresnel lens is obtained by modulating the phase of a classical lens by 2π which is equivalent to modulate the thickness of a classical lens by e . It replaces the curved surface of a conventional lens by a series of flat concentric rings. A Fresnel lens is illustrated on Fig.1.

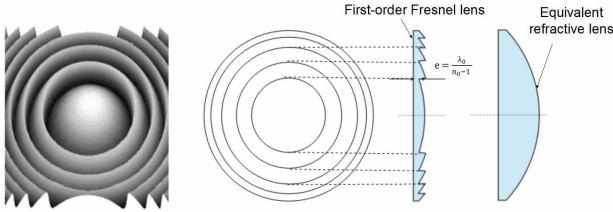


Figure 1. Scheme of a first order Fresnel lens and the equivalent classical lens. The Fresnel lens is much less thick than a classical lens.

When we illuminate the entire first order Fresnel lens, it will not have the refractive behavior of a classical lens but rather a diffractive behavior. The lens acts as a diffractive grating and each incident ray will diffract in different orders. The amount of energy diffracted in each order is more or less important according to its diffraction efficiency [3]. The diffraction efficiency of a given order m at λ is given by the following equation:

$$\eta_{m,\lambda} = \text{sinc}^2\left(\alpha \frac{\lambda_0}{\lambda} - m\right) \quad (3)$$

where α is given by:

$$\alpha = \frac{n(\lambda) - 1}{n(\lambda_0) - 1} \quad (4)$$

In the following, we can assume that the dispersion of the material is negligible so $\alpha \approx 1$ since infrared materials like silicon have small dispersion [4].

At the blazed wavelength λ_0 , the first order of diffraction has 100% efficiency and the lens is equivalent to a classical refractive lens. That's why we call it a *first order* Fresnel lens. At any other wavelength λ , the first order is no longer 100% efficient. The lens diffracts in other orders, each one having a weight given by the diffraction efficiency at λ . However, we have estimated that almost all the energy is diffracted in the first order and other orders are considered as parasitic. In some cases we will have to take into account this orders, for example when we illuminate just a few discontinuities, typically less than three [5].

Considering that all the first order Fresnel lens is illuminated and that the lens only diffracts in the first order of diffraction, its focal length at λ is given by:

$$f(\lambda) = \frac{\lambda_0}{\lambda} f_0 \quad (5)$$

The focal length widely depends on the wavelength. The focal spread yields to a defocusing aberration, or axial chromatism, in the focal plane. The main specificity of a Fresnel lens is that its focal length is inversely proportional to the wavelength, thus it exhibits a negative chromatic dispersion. Knowing that the chromatism of a classical refractive lens is positive, the traditional interest of a first order Fresnel lens consists in associating it to a classical lens in order to compensate its chromatic aberration [6].

Our goal is to design a cheap camera using only one thin lens. A broadband infrared camera made of a single first order Fresnel lens would have too much chromatic aberration. Fortunately, the large field of view of the camera we want to design will lead to a short focal length. Reducing the focal length, the axial chromatism will decrease accordingly. However it will still be too high.

The solution to limit chromatic aberrations is to use a high order Fresnel lens [7], [8], [9]. Some other solutions are presented in [6] and [10] but they often need to use several optical elements and sometimes with different materials. These methods are too expensive to be used in our applications.

3. THE HIGH ORDER FRESNEL LENS

The principle of the high order Fresnel lens was mentioned in 1961 in a footnote of an article by Miyamoto [11]. His interest was to increase zone sizes to make the lens easier to manufacture. Then these components have been described more precisely in order to reduce chromatic aberrations of the traditional first order Fresnel lens [7], [8], [9].

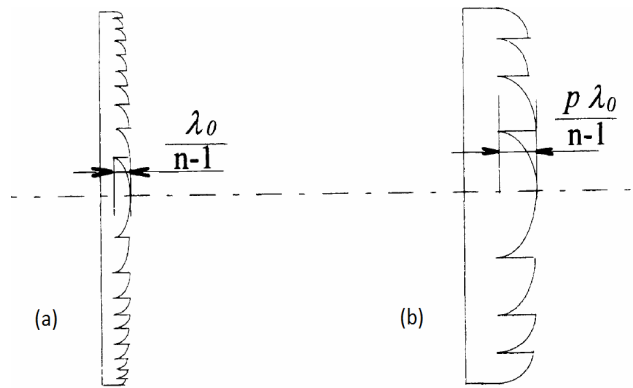


Figure 2. (a) A first order Fresnel lens. (b) A p-th order Fresnel lens. [7]

A p-th order Fresnel lens ($p > 1$) is a Fresnel lens whose phase jumps are $2\pi p$ at the blazed wavelength λ_0 and whose groove depth is p times the groove e of the first order Fresnel lens. The phase introduced by the lens at λ_0 is the phase of a classical lens modulo $2\pi p$. The width of the zones is p times the width of the zones of a first order Fresnel lens; at fixed diameter, it has fewer discontinuities. It is illustrated in Fig.2.

This lens is made to be 100% efficient in the p -th diffraction order at wavelength λ_0 . Its particularity is that at some wavelengths different from λ_0 , we can find an order of diffraction m different from p for which the diffraction efficiency is 100% again. Neglecting the dispersion of the material, that particularity is summarized in the following relationship which gives the diffraction efficiency of a diffraction order m at λ [2]:

$$\eta_{m,\lambda} = \text{sinc}^2\left(\frac{\lambda_0}{\lambda} p - m\right) \quad (6)$$

The focal length of the p -th order Fresnel lens is changed into:

$$f(\lambda) = \frac{p\lambda_0}{m\lambda} f_0 \quad (7)$$

where m is the order for which the diffraction efficiency is maximum at λ .

It is interesting to notice that for some resonant wavelengths λ satisfying Eq.8 we can consider that the order m is 100% efficient (see Eq.6) and incoming rays interfere constructively in the focal plane given by f_0 (see Eq.7).

$$\lambda = \frac{p\lambda_0}{m} \quad (8)$$

For each one of those wavelengths, rays will all focus at the same distance f_0 from the component and chromatic aberrations are set to zero. For other wavelengths chromatic aberrations are not negligible but are less important than in the case of the first order Fresnel lens.

Up to now, Fresnel lenses have almost never been used alone for broadband imagery systems because of their chromatic properties. By increasing the order of the lens, we are able to minimize the unwanted effects of chromatic aberrations. During the last decades, improvements in fabrication methods have been achieved and we are now able to design a wide range of micro optics. However we have to keep in mind the technological limits which will prevent us to design lenses that have too large groove depths.

4. OPTICAL DESIGN

In this paper, we want to discuss an optical architecture which would permit to design a cheap broadband very wide field of view infrared camera using a single high order Fresnel lens.

Some design strategies have been presented in the past to reduce the volume and the cost of optical architectures. The main strategies are either to design multichannel optical systems [12] or to design architectures made of two lenses,

generally in a Petzval or in a retrofocus configuration [13]. Adapting these architectures to our works would yield to complicated and expensive systems. We want to go further by designing a cheap camera made of only one diffractive lens.

To our knowledge, only few documents present an optical system made of only one diffractive lens for broadband and wide field of view imagery applications. In [8], Sweeney used a system made of a single high order Fresnel lens ($p=15$). However his camera is adapted for the visible spectrum and has a narrow field of view. Moreover, image quality is yet degraded at a quite small view angle.

The landscape lens configuration is an interesting one when we have to use a single lens to build a wide field system [14]. It consists in one diaphragm followed by an optical component and the detector. It is of particular interest to minimize the geometrical aberrations of a camera [15] and more particularly of an infrared camera. Indeed, it will correct the astigmatism which is the predominant aberration of an infrared system. Due to the high equivalent refraction index of the materials used in the infrared, other aberrations remains quite low. The field curvature, which decreases when the index increases, will be quite small and coma and spherical aberration will be minimized by making the lens profile aspheric. Authors in [15] have shown that a diffractive lens is equivalent to a thin lens whose index of refraction is infinite. Thus, in our case where the lens is a diffractive optics, field curvature, coma and spherical aberration will be reduced accordingly.

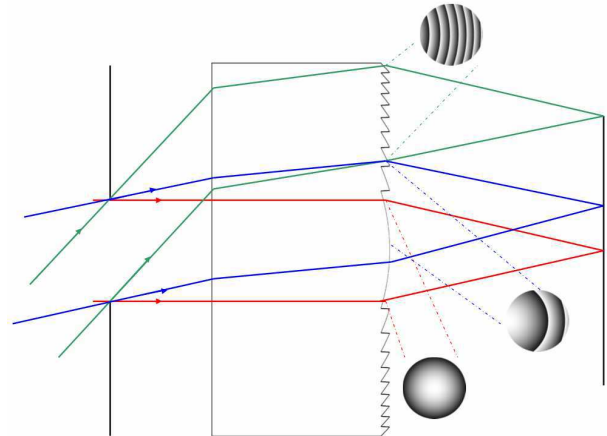


Figure 3. Illustration of the optical architecture we have selected. The landscape lens configuration illuminates an off-center non symmetric part of the Fresnel lens. It permits to limit the number of discontinuities illuminated across the field (Red : $\theta=0^\circ$; Blue : $\theta=30^\circ$; Green : $\theta=65^\circ$).

In order to minimize the chromatism of the Fresnel lens, the diffractive lens that we use is a high order Fresnel lens. Moreover, the architecture we have chosen will allow to limit the number of

discontinuities enlightened as illustrated in Fig.3. By that way, we will minimise the effects of diffraction. In [5] and [16], research groups have shown that when we don't illuminate the entire lens we observe a transition between a purely refractive behavior (when no discontinuity is illuminated) to a purely diffractive behavior (when about three or more discontinuities are illuminated).

We have used the optical design software Zemax to build a broadband infrared camera based on a landscape lens configuration. The lens is a f/1.5 high order Fresnel lens in silicon. The thickness of the lens is 1 mm. The camera has a wide field of view around $\pm 65^\circ$ and a short focal length around 1 mm. The camera has been designed to operate in LWIR region from 7 to $14\mu\text{m}$ and it is compatible with a small cheap uncooled detector 80×60 pixels with $25\mu\text{m}$ pixel-pitch. On the field's edge, about 6 discontinuities are illuminated which is not too much. The camera is suitable for low-cost surveillance applications.

5. THE PROTOTYPE

A prototype of our camera has been realized. It is illustrated on Fig.4. The Fresnel lens in silicon has been made by diamond machining by Savimex company. The master of diamond tooling permits to generate a continuous profile for diffractive lenses and this profile is the best guarantee for high image quality. So it is the best candidate to make first experimental measurements. However, such a process is too expensive and time consuming [17]. In the future, we will rather consider the method which consists in etching a silicon wafer. This fabrication process would allow to massively produce a high number of lenses by photolithography. Another approach is to design a system based on a Gasir or polyethylene Fresnel lens which could be fabricated by molding process. A mold with low roughness would be designed by diamond machining and then large number of lenses of high optical surface quality could be massively replicated. Thus fabrication costs would be consequently reduced.

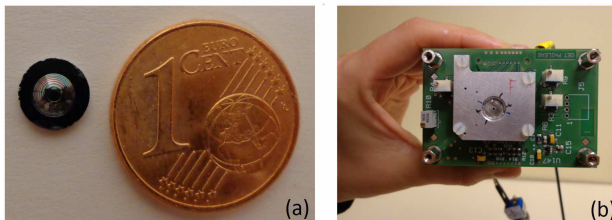


Figure 4. (a) Picture of the Fresnel lens. (b) Picture of the camera.

Our camera prototype works with a microbolometer composed of 160×120 pixels with $25\mu\text{m}$ pixel pitch but the image is done only on a small part of the detector array, about 80×60 pixels.

6. EXPERIMENTAL VALIDATION

We have realized several experimental measurements to evaluate the optical performances of our camera. We have measured the Noise Equivalent Temperature Difference (NETD) of the system as well as its Modulation Transfer Function (MTF).

6.1. NETD

The NETD of our complete system, lens and detector, is measured around 220mK at f/1,5 which corresponds to about 100mK at f/1. On the other hand, the NETD of the detector alone has been measured and is equal to 75mK at f/1. The small degradation of the NETD that we obtain by adding the lens in front of the detector is due to the absorption of silicon. However we see that the degradation of the NETD is not so important. The transmission of a silicon plate with a thickness of 1mm is shown on Fig.5 (curve 4) and we effectively notice that the transmission is still good in the LWIR region, from 7 to $14\mu\text{m}$. Of course, curves 1, 2 and 3 show that better performances could be obtained by decreasing the thickness of the plate, which is possible by using a photolithographic process. Fig. 5 also shows that silicon has an important absorption around $9\mu\text{m}$ but that this absorption peak can be reduced by using Float Zone Silicon.

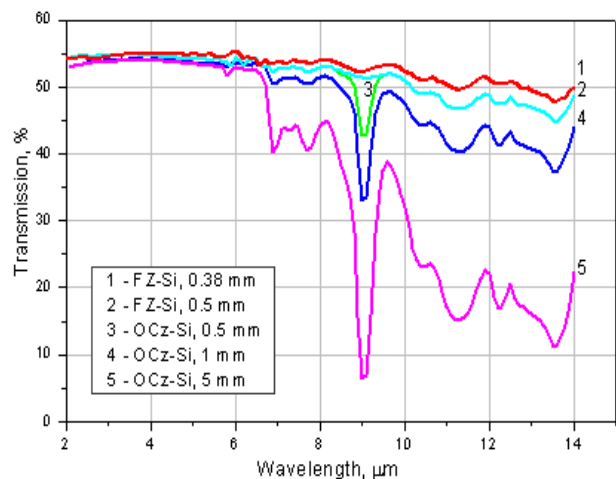


Figure 5. Transmission of OCz-Si and FZ-Si with respect to thickness [18]

So the use of a thin lens in silicon can be an interesting choice for the design of a cheap uncooled LWIR camera. Indeed, the sensitivity of our camera would have been much more degraded using a conventional thick lens.

Planar optics allow to use silicon lenses in LWIR which can be fabricated at wafer level and which need few material. These two points considerably reduce the price of the optical system.

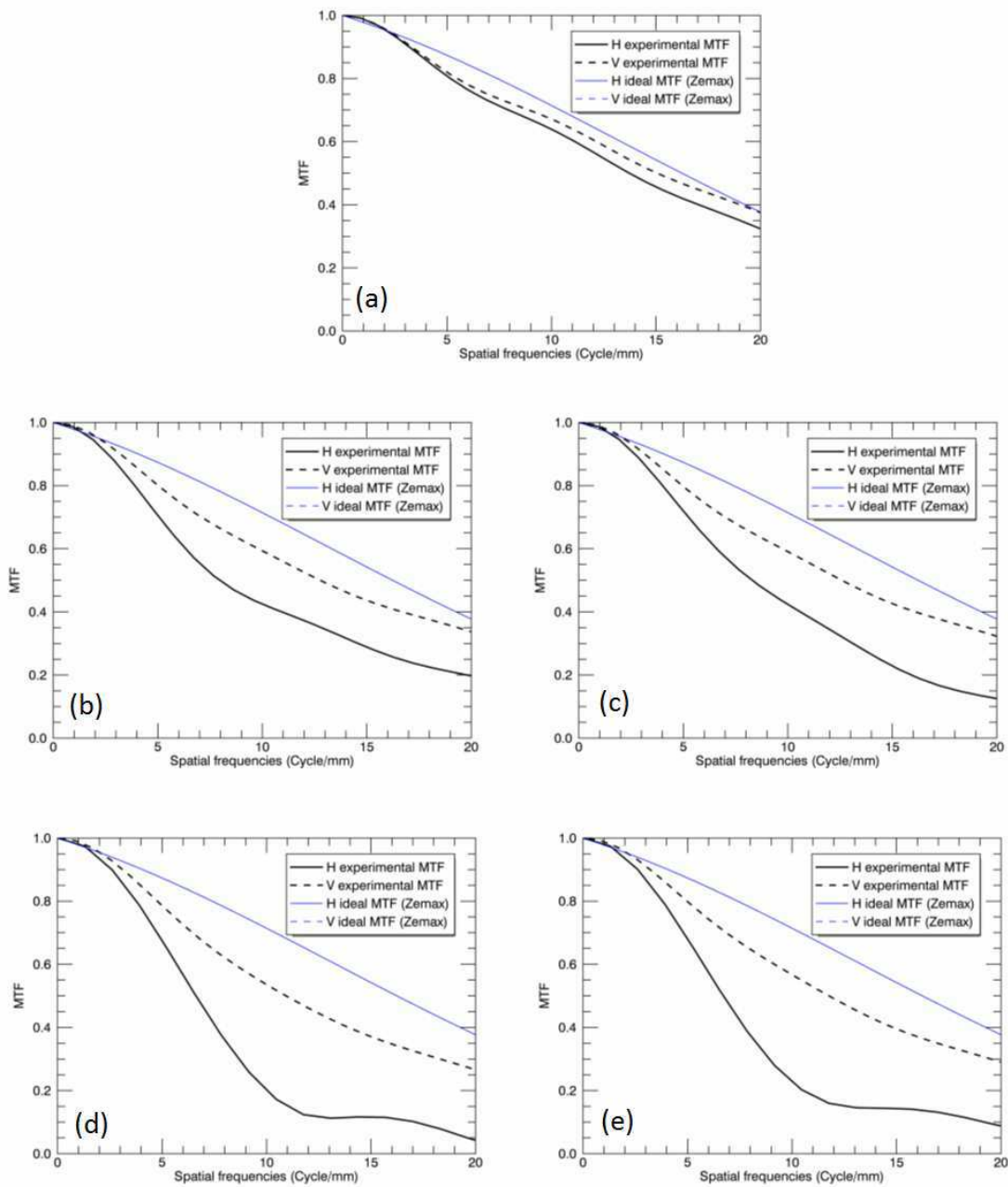


Figure 6. MTF measurements for different field angles (FOV).
 (a) FOV = 0°; (b) FOV = -30°; (c) FOV = +30°; (d) FOV = -50°; (e) FOV = +50°

6.2. MTF

We have measured the MTF of our camera by using the Spot Scan method. Our test bench is the following: a black-body illuminates a pinhole placed at the object focal plane of a collimator. The camera makes the image of that pinhole on the detector. Then we slightly move the camera in front of the collimator by sub-pixel shifts to well sample the Point Spread Function (PSF). The Fourier Transform of the well-sampled PSF gives the MTF. Measurements have been done for different field angles and are compared to the FTM calculated from an ideal planar lens estimated by Zemax software (see Fig.6). This ideal planar lens does

not take into account phase jumps between the discontinuities and by this way, do not produce the limiting chromatic aberration. The plots of Zemax FTM illustrated in Fig.6 take into account the transfer function of the pixel. Moreover, the spatial frequency axis has a maximum value of 20 Cycles/mm, which corresponds to the Nyquist frequency of our detector.

We observe that experimental MTF slightly falls compared to the ideal curves provided by Zemax. We could predict that point considering the fact that the Fresnel lens from Zemax is an ideal flat lens and doesn't model the discontinuities and the chromatism of the lens.

For each field angle, the experimental FTM is only degraded in one direction which is the direction of the discontinuities. This is due to the fact that our system illuminates an off-center non symmetric part of the Fresnel lens. The optical performances of our camera are more and more degraded in that direction when the field angle increases, so when we illuminate more and more discontinuities. In this way, we see the transition between a purely refractive lens and a purely diffractive lens.

Keeping in mind that the camera is dedicated to surveillance applications where priority is given to the price of the camera even if the picture resolution is reduced, we can consider that the degradation of the FTM remains acceptable.

6.3. Images

Some images have been recorded with our micro camera. In Fig.7 we can see on the left a picture taken in an office for surveillance applications (people detection and counting, etc). On the right is a picture taken in a car which could be used for automotive applications (driver monitoring, intrusion detection, etc). In the two images we can detect people and see some details of the scene. Our camera is thus proper for surveillance applications.

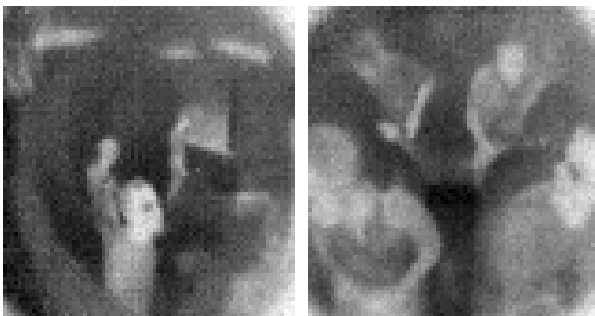


Figure 7. Pictures taken with our domotics camera.

7. CONCLUSION

We have designed, manufactured and characterized a cheap infrared micro camera for surveillance applications. The imager has a wide field of view, operates in LWIR region from about 7 to 14 μ m and is compatible with a cheap uncooled microbolometer 80x60 pixels with 25 μ m pixel pitch. The design would easily be adapted to be used with the last cheap detector 80x80pixels with 34 μ m pixel pitch manufactured by ULIS. The prototype is based on a landscape lens configuration. It is an optical system composed of a diaphragm, a single optical component and the detector. The optical component is a high-order Fresnel lens. This lens is in silicon and can be fabricated using photolithography. The use of silicon in the LWIR spectrum region is made possible because the lens is very thin and thus the absorption will be rather low. NETD measurements show that the sensitivity of the camera is comparable to the one

of the detector alone. The degradation of the sensitivity due to the absorption of silicon is not too important. In another hand, FTM evaluations at different field angles show that the image quality is quite good, the degradation at the edge field being acceptable. Our prototype is well-suited for low-cost surveillance applications where priority is given to the reduction of the price and the image quality can be slightly reduced. Our design could be adapted using unconventional very inexpensive materials such as Gasir or polyethylene which can be molded. Polyethylene can't be used in traditional systems with thick refractive lenses because it would be too absorbing.

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