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MICRO-OPTICS TECHNOLOGY AND SENSOR SYSTEMS APPLICATIONS

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ABSTRACT

The current generation of electro-optical sensors utilizing refractive and reflective optical elements require sophisticated, complex, and expensive designs. Advanced-technology-based electro-optical sensors of minimum size and weight require miniaturization of optical, electrical, and mechanical devices with an increasing trend toward integration of various components. Micro-optics technology has the potential in a number of areas to simplify optical design with improved performance. This includes internally cooled apertures, hybrid optical design, microlenses, dispersive multicolor microlenses, active dither, electronically controlled optical beam steer, and microscopic integration of micro-optics, detectors, and signal processing layers. This paper describes our approach to the development of micro-optics technology with our main emphasis for sensors applications.

1.0 INTRODUCTION

The current generation of electro-optical sensors, with refractive and reflective optical elements, requires sophisticated designs which are complex and expensive. The system complexity, which drives the cost, is a combination of optical design, focal-plane design, processor design, etc. A technology breakthrough in any of these areas would significantly reduce the cost and enhance the performance of these sensors.

The area of micro-optics technology (MOT) has potential for a breakthrough in a number of areas. In micro-optics technology, micro-optical components are fabricated through a variety of means, including photolithographic methods for multilevel and analog lenses. In binary optics, elements are fabricated using a series of binary masks. This is a proven technology for elements which operate in the infrared over a small wavelength band, but is infeasible for use over a wide wavelength band or shorter wavelengths because of the large number of mask sets required or too-small feature sizes on the masks. Micro-optics fabrication for elements operating under the latter conditions will require the development of a new etching technology utilizing grayscale masks. (One grayscale mask can replace several binary masks.)

On a macroscopic scale, hybrid lenses using diffractive structures superimposed on refractive optical elements can achromatize and/or aspherize the optical train and improve optical performance with few optical elements. On a microscopic scale, layered microscale integration will combine microlens layers with analog signal processing elements to produce Photonic-Z plane technology, which can enormously enhance optical and signal processing capability. A new systems design application is an agile beam steering (ABS) unit used for laser scanning and also as part of an inexpensive sensor design for smart weapons. A properly designed microlens array with additional dispersion effects will allow multicolor focal-plane arrays (FPAs). Simultaneous multicolor operation for an advanced FPA has the potential for realtime temperature discrimination. We have initiated an R&DD effort for micro-optics technology development and focused on the most important system applications as outlined in Figures 1 and 2.

In this paper, we will discuss our approach to micro-optics technology development and discuss several novel applications of micro-optics to sensors. We will not address system design issues associated with advanced technology based sensors, but will focus on the applicability of micro-optical elements and their benefits to the sensor.

2.0 MICRO-OPTICS TECHNOLOGY DEVELOPMENT

There are several options available for micro-optics that can be used in system applications. They fall into three broad categories: refractive, diffractive, and hybrid elements. Design and fabrication also affect the resulting elements. Elements can be designed either as Fresnel or non-Fresnel, and can be fabricated either as multilevel or analog (smooth).

Refractive elements are the type ordinarily associated with optics and work by redirecting light by refraction at media interfaces. Refractive lenses are typically spheric surfaces with aspheric corrections to mitigate aberration effects.

Diffractive elements redirect light by creating phase differences in the optical field using diffractive structures. At a single wavelength, diffractive elements can be designed which perform identically to refractive elements. Over a wavelength band, however, diffractive elements introduce chromatic effects due to the fact that the optical path differences created by their structure are wavelength dependent. These can be used to advantage to create dispersive elements (as, for example, in the familiar diffraction grating) when information contained in a wavelength band is important.

Hybrid elements are refractive elements with diffractive structures etched onto their surfaces to perform specified functions. For example, material dispersion has a wavelength dependence opposite to that of diffractive dispersion. By etching a diffractive structure onto a refractive microlens, it is possible to make these effects negate each other, allowing chromatic correction by use of a single hybrid element (using a single material) instead of a multiple refractive element (using different materials). This leads to a concomitant savings of weight and cost of the optics.

Fresnel elements are elements whose thicknesses have been reduced modulo a material thickness equivalent to a change of 2π in the optical phase. A 2π phase change is unseen by the optical wave so that the Fresnel element acts the same as the non-Fresnel element upon which it is based. Because the optical path length through the material is wavelength dependent, the 2π

phase changes can only occur at a selected ("design") wavelength and its harmonics. At all other wavelengths the Fresnel element introduces chromatic aberrations. Thus the Fresnel element is ideally suited only for monochromatic light.

In the fabrication of micro-optics by photolithographic techniques, a standard method is to etch the element surface into a substrate using a series of masks made up of opaque and transparent regions. The regions are designed to give a multilevel approximation to the element surface. A set of M masks yields 2^M levels and the resulting elements have acquired the name "binary optics." The multilevel structure reduces the efficiency of the elements, although for Fresnel elements, fabrication using three masks yields 95% efficiency.[1] New techniques are being proposed to fabricate more efficient elements. One of these, grayscale fabrication, has been pioneered by Lockheed in conjunction with Philips of England and will be discussed below. In grayscale fabrication, only a single mask is used to fabricate an analog element.

The different options and types of micro-optical elements are shown in Figure 3.

2.1 TECHNOLOGY DEVELOPMENT OBJECTIVES

The Lockheed Research & Development Division (R&DD) has a continuing multiyear independent research program for the development of micro-optics technology. The long-term objectives of the program are to develop optical design methodology and computer-aided design tools for diffractive/refractive micro-optical elements, designed and fabricated either as analog elements or with multilevel approximations; to implement photolithographic fabrication technology for producing optical elements on different substrates as required for various research areas; and to evaluate these optical elements or subassemblies in the laboratory.

Micro-optics technology has potential applications in a vast number of areas. Our current efforts are focused on eventual integration of micro-optics devices to achieve the full integration required for an advanced technology sensor. Our technology approach is broken down into four main tasks. These are (1) Analysis and Computer Software Development, (2) Fabrication Process Development, (3) Laboratory Evaluation of Micro-Optical Elements, and (4) System Applications of Micro-Optic Devices.

2.2 ANALYSIS AND COMPUTER SOFTWARE DEVELOPMENT

Because of the large variety of options and types of micro-optics, it has been necessary to develop generic methods and tools to analyze different elements. A sampling of different kinds of elements we have had under consideration is shown in Figure 4.

Our analytical methods are based upon the scalar wave theory of physical optics.[2] These methods are applicable to all elements where polarization is unimportant (as is the case for most of the elements shown in Figure 4). We have developed analytic techniques for dealing with analog and multilevel elements, designed as either Fresnel or non-Fresnel. These techniques are a great help in paramaterizing the performance of an element. For example, if an element is characterized by a certain set of parameters, its corresponding Fresnel element will introduce one additional parameter, the ratio of the design wavelength to the radiation wavelength. Constructing a figure of

1. Swanson, G. J., "Binary Optics Technology: Theory and Design of Multilevel Diffractive Optical Elements," *Lincoln Lab. Tech. Rep. 854*, Aug 1989.
2. Goodman, J. W., *Introduction to Fourier Optics*, McGraw Hill, New York, 1968.

merit comparing the Fresnel element performance to the non-Fresnel element performance is a straightforward matter. This figure of merit can be plotted in parameter space and the result can be used to determine when the chromatic effects introduced by the Fresnel element become too severe. This approach can save an enormous amount of time over an alternative approach where the performance of the Fresnel element is calculated numerically over a range of parameters to determine a "best" performance. An example of the analytic approach applied to the dispersive microlens is given in Reference 3.

In addition to analytical tools, we have developed a host of computer codes to treat wavefront propagation through micro-optical elements. These codes are used when more detail is needed than can be obtained from simple analytical models. For example, integration of micro-optics on a focal plane requires knowledge of how much light falls on a proposed detector layout. This is most easily calculated using numerical codes. Another example is when one has to deal with more complex topologies (such as hexagonal or skewed elements) where analytic methods are too cumbersome to be useful.

More sophisticated codes are also used in the optical design of some micro-optics concepts. For example, the concept of an agile beam steering unit is shown in the lower left corner of Figure 4. Here, a pair of microlenses are displaced relative to each other. This causes a deflection of a beam of light traveling through the lens pair. The deflection is dependent upon the size of the displacement, so as one lens is scanned behind the other, the beam also scans up and down. In a first-order approximation, the scan can be paramaterized by the displacement and the diameter and f-number of the lenses. To incorporate this concept into a real-world application, system-defined requirements must be met (e.g., no vignetting, minimization of aberrations in the optical train). This can only be done using computer codes. As an example, this concept was extended to develop the two-dual-sided-element, agile-beam-steering unit cell shown in Figure 5. This unit cell is capable of scanning over a $\pm 20°$ field of regard without vignetting. The work was performed using the Lockheed OPTIMA ray tracing code.

We have also developed codes to determine micro-optical elements that modify a wavefront to give a desired phase or intensity distribution. Types of elements that fall into this category are shown in the last two columns of Figure 4. The programs operate by iterating back and forth between the element and a focal plane, applying constraints until the desired distribution is reached. The resulting "phase plates" can be used, for example, for wavefront aberration correction or for beam shaping. An example of a phase plate that is used as a spot-array generator is given in Figure 6.

Finally, we have developed a set of codes for generating the binary mask sets needed for the photolithographic fabrication process. The codes generate the required masks for any specified micro-optical element surface and are flexible enough to handle any number of masks along with a specified mask feature size.

2.3 FABRICATION PROCESS DEVELOPMENT

In the past few years, new developments in semiconductor industry process technology have made it feasible to generate diffractive and refractive micro-optic components. These process technologies are submicron photolithography and large-scale dry etching.

3. Herman, B. and G. Gal, "Theory of Dispersive Microlenses," Conference on Binary Optics, Huntsville, AL, Feb 1993.

In Reference 4 we reported the progress and research programs for micro optics fabrication at Lockheed and Philips U.K., hence only a summary is given here.

For multilevel elements, the etching must produce vertical side walls well registered with mask features (i.e., no undercutting or shadowing) or some lens area is lost. The etching must also produce smooth surfaces at the bottom of the etched area. Finally, the etch rate (or, equivalently, etch depths) must be reproducible for a production process. The two technologies that satisfy these requirements are reactive ion etching (RIE) and ion beam milling.

In RIE, ions produced in a plasma discharge react with a substrate material to form a volatile compound which is then removed from the system. The RIE process is highly anisotropic so that vertical side walls are obtained at the multilevel steps.

In ion beam milling, a collimated, uniform beam of inert ions, extracted from a plasma discharge, bombards the surface of a substrate. The momentum transferred by these ions breaks the bonds of the substrate surface atoms. Material not protected by a mask is selectively etched away. Etch features down to 0.2 μm and with aspect ratios of 5:1 can be achieved.

We have fabricated Fresnel microlens arrays for operation at a wavelength of 10.6 μm in both Si and CdTe substrate materials using binary masks. Both RIE and ion beam milling technologies were utilized. The optical performance of the lenses was measured to be diffraction limited. Sections of the eight-level Si and CdTe arrays with a 100-μm pixels are shown in Figure 7.

Two approaches are available for continuous curved surface micro-optics element fabrication. Both rely on the differential milling rate of photoresist and substrate material. In both approaches, only one photolithographic step is required so that problems of multiple mask registrations are avoided. The thickness profile of the photoresist is controlled in one case by the surface tension of isolated circles of photoresist during a controlled bake and in the second case by "half-tone grayscale" exposure control of the photoresist pattern.

In the first case, photoresist patterns with diameters in the range of 60 to 250 μm are delineated by conventional photolithographic techniques. They are then baked at a temperature higher than the glass-transition point of photoresist so that spherical contours are generated by the effect of surface tension on the photoresist surface. Then the substrate is subject to Ar ion-beam milling. During the milling, the spherical mask contour is transferred to the substrate surface. While this technique is effective and straightforward, it is severely limited in that only spherical (and closely related) shapes are possible. In particular, it is not possible to incorporate diffractive structure superposed on the basic refractive optical shape, as required for dispersive microlenses.

The second option is the half-tone grayscale approach. The desired thickness profile is modeled by a related submicron half-tone photoresist exposure pattern. The photoresist exposure and development process is adjusted so that a smooth contoured photoresist mask is produced with (almost) completely controlled topography. Differential milling of photoresist and substrate is again used to transfer the contour to the substrate.

Grayscale fabrication technology is essential for the fabrication of non-Fresnel analog dispersive microlenses. This type of microlens is ideally suited for multicolor focal planes, and is currently under research and development in our laboratory.[3] An example of a microlens designed to operate in the LWIR spectral region is shown in Figure 8.

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4. Anderson, W., J. Marley, D. Purdy, and G. Gal, "Fabrication of Micro-Optical Devices," Conference on Binary Optics, Huntsville, AL, Feb 1993.

The analog microlens was fabricated in silicon. Figure 8 indicates the criticality of the grayscale single mask technology to generate smooth surface with vertical steps. The dispersive microlens array is currently under experimental performance evaluation.[5]

A third area for fabrication technology development is that of microchannel fabrication. Microchannel fabrication is necessary when cooling channels must be introduced to a micro-optic component so that the component can be kept at a required operating temperature. A variety of technologies are available for microchannel fabrication. Technology choice is determined by required channel dimensions. The technologies are: plasma or dry etching (appropriate for depths less than ~20 μm), anisotropic wet etching (appropriate for depths of 10 to 1000 μm with depth to width ratios 10:1 or greater), laser machining (appropriate for widths greater than 25 μm), and precision wafer sawing (appropriate for widths greater than 175 μm).

An example of microchannels fabricated in silicon using a hot KOH etch is shown in Figure 9. There is the order of 100:1 etch rate difference between the weakly bonded $\langle 110 \rangle$ planes and the strongly bonded $\langle 111 \rangle$ planes. By aligning the channel direction along the $\langle \bar{1}21 \rangle$ direction of a $\langle 110 \rangle$ oriented wafer, the channel walls will be the weakly etched $\langle 111 \rangle$ planes. The 100:1 directional etch ratios require alignments to the order of 0.1°. The microchannels were etched into one silicon substrate and another silicon substrate was fusion bonded to the top of the etched substrate to close off the microchannels.

More details of the fabrication process technology we have developed at Lockheed can be found in Reference 4.

2.4 LABORATORY EVALUATION

LMSC R&DD has built up facilities over the years for testing different types of microlenses. The experimental setup, shown in Figure 10, provides a direct measure of the point-spread function (PSF) of any individual microlens or a microlens array. The basic idea is to illuminate a microlens array with a collimated beam, magnify the PSF onto a detector, and record and control the experiment using a computer.

The light source is a laser operating at the appropriate wavelength. The source is chopped at 1 kHz by a mechanical chopper. The laser sources provide large amounts of power, allowing the measurement in detail of the wings of the PSF that might interfere with neighboring lenslets. The dynamic range can be more than six orders of magnitude. For wideband testing, the lasers will be replaced by a blackbody source and spectral filters.

An all-reflecting microscope objective magnifies and relays the PSF to an appropriate detector (e.g., a Si photodiode). The objective provides a standoff distance of 8 mm between the plane of focus and the front of the microscope. Varying the separation of the objective and detector changes the magnification and the effective area covered by the square area of the detector. The output of the detector is preamplified and sent to a lock-in amplifier. Synchronous detection reduces the background noise.

The output of the lock-in amplifier is measured by an analog-to-digital converter located in a computer. The same computer controls motor-driven xyz translation stages that position the microlens array. By moving the array, the detector sees different portions of the microlens PSF. A

5. Shough, D., B. Herman, and G. Gal, "Measurements of Microlens Performance," Conference on Binary Optics, Huntsville, AL, Feb 1993.

program on the computer scans the transverse position of the array, pauses until the output of the lock-in amplifier has had time to stabilize, measures the voltage output, and then steps to the next scan position.

The PSF of an isolated CdTe Fresnel lens shown on Figure 7 has been measured at LMSC using a 10.6 μm CO_2 laser, and the result is shown on Figure 10b. This measurement is to be compared to the theoretical PSD, which has been convolved with the 16-μm detector size. The difference between the measured and theoretical results is hardly distinguishable.

Due to the multicolor nature of the next generation of micro-optics, we are adding the capability to vary the wavelength at which we test the lenses. Our laboratory has been updated to multicolor capability with the inclusion of lead-salt lasers operating at 8, 10 12, and 14 μm. Lasers are also available for testing in the 3- to 5-μm MWIR region. More details about our laboratory setup can be found in Reference 5.

3.0 SENSOR SYSTEMS APPLICATIONS

The next generation of multispectral seekers may include the capability of realtime, on-board color discrimination, along with other smart-pixel, on-focal-plane processing capabilities that will enhance data throughput. Neural-network-technology-based analog circuits for acquisition, centroiding, nonuniformity correction, tracking, and image motion compensation are potential candidates for smart-pixel-integrated analog-signal-processing designs for semi-autonomous sensors. Opto-electronic signal processors for these seekers will consist of different layered components, each performing specific tasks. The design goal for these seekers is to produce compact, lightweight designs with optimal performance. Feed-forward/backward closed control loops may also be included in the Z-layered integration. The monolithic integrated sensor system may be designed for strategic, tactical and/or commercial applications such as smart robotic sensors.

3.1 INTERNALLY COOLED MICROLENS ARRAY APERTURE

The first component for the monolithic integrated system may be the internally cooled aperture of the seeker, which may be enhanced with a built-in step/stare capability to address a large field of regard (FOR). This aperture will function as an internally cooled protective window for endoatmospheric encounters. For exoatmospheric missions, the system would operate in the longer wavelength region; hence, it is desirable to cool the aperture to reduce background noise due to the optics thermal self-emission. For a generic research and development effort we have addressed the optical design issues of an internally cooled microlens array aperture. The use of microlens arrays allows some volume of the window to be optically inactive. This will allow for the inclusion of microcooling channels through which heat can be removed.

Development of an internally cooled microlens array aperture[6] requires the use of innovative technologies and novel optical designs. Technology areas include micro-optics and cooling channel fabrication, cooling systems, and opto-mechanical integration. Novel optical designs are required to meet thermal, FOR, size, and weight requirements.

There are two basic conceptual aperture design options. These fall into the categories of staring arrays and agile beam steer scanners (phased arrays).

6. Gal, G., B. Herman, H. Morrow, W. Anderson, I. Hsu, and D. Stubbs, "Seeker Multispectral Atmospheric Technology (SMART) Window Development," *AIAA-92-2804*, AIAA SDIO Annual Interceptor Technology Conference, Huntsville, AL, May 1992.

The staring array shown in Figure 11 is limited in its FOR by the fixed field of view (FOV) of the microlenses. The FOR can be increased either by the maneuver of the sensor orientation, which may not be feasible for many applications, or by scanning. We have studied an innovative design option that will include an agile beam steering unit to achieve the required FOR using an optomechanical step/stare device which includes a feed backward control subsystem design.

The idea of using microlens arrays as the basis for an ABS unit has been presented by Goltsos and Holz.[7] Our implementation uses a different design layout (Figure 12). Shifting one of the arrays allows the angle of the incident light to vary, thus extending the FOR. The angle shifts obtained are proportional to the microlens sizes, not the aperture size, so that a large range of angles can be obtained using only micromovements. In our conceptual design, we have achieved scanning over a range of $\pm 20°$. Microlens arrays in the ABS again allow for microcooling channels.

Our choice of implementing an ABS in the window to increase the FOR posed fundamental design problems which have never been addressed before. First, we designed a unit cell train in the optical layout. Upon successful completion of the unit cell design, our effort focused on the assembly of unit cell trains into a 2-D aperture array and the multiaperture effect on the transmitted wavefront and image quality.

The afocal design of the unit cell train will allow either a transmitter or receiver mode of operation and was approached from two different directions: (1) Unbiased unit cell train design for high performance shown in Figure 5. The approach was to discover the best design form for a cell train which met the imaging requirements one step at a time, gradually increasing the angular requirements of the design. (2) Large look angle bias (LAB) required for sloped surfaces. A 3×3 element array segment of the aperture is shown in Figure 12. The approach was to quickly generate all the angular requirements and then gradually improve the imaging performance.

The purpose for approaching the cell train design in this manner was so that the best ideas from the different approaches could be combined in a final design. We have concluded that the unit cell design option shown on Figure 5 will provide a better performance. The design included a detailed thermalization trade study and the cooling provided through the microchannel were sufficient to to yield excellent thermal performance.

Phased array issues are important because a wavefront entering a microlens array obliquely will be stepped upon its exit. If the steps are an integral number of wavelengths apart, the reconstructed image will suffer no detrimental effects from this stepping. For a given wavelength, this condition will occur only at selected angles (eigenangles). Over a spectral band, this stepping will introduce aberrations even at the eigenangles because the steps are wavelength dependent.

Phased array issues for imaging were addressed by developing computer tools to perform numerical optical experiments. The current state of the tools is such that we can analyze arrays as large as 9×9 (81 cells) either monochromatically or polychromatically. The only limits on the number of wavelengths and array sizes we can treat are those imposed by computer memory and time constraints.

A high-performance cell-train with -1 magnification has been successfully designed. This two-element form has a 40° full FOR and room for cooling channels. It scans without a trace of vignetting. The image is diffraction limited over a 4° field and over the full FOR. The LAB of this

7. Goltsos, W. and M. Holz, "Agile Beam Steering Using Binary Optics Microlens Arrays," *Optical Engineering*, Vol. 29, No. 11, pp. 1392-1397, Nov 1990.

design is zero. It has also been set in arrays up to 9 $\times$ 9 for mosaic wavefront image formation investigations. The polychromatic PSF in the MWIR for the 9 $\times$ 9 array in the unscanned position is also shown in Figure 12. The polychromatic performance proved to be inadequate and additional micro-optical elements are required for chromatic phase correction A detailed design study is currently underway and preliminary results indicate that the phase corrector subassembly can be successfully implemented.

Several important design lessons were learned while designing the ABS. The scan element must move in an arc to maintain wavefront collimation. The internal focus should be inside the first element to give the best wavefront performance. All four surfaces need high-order aspherics; the outer surfaces on the pupils required 8th order polynomial correction.

We have achieved a 55° LAB with ±20° FOR scan. The −1 magnification cell train required three elements. Several of the surfaces were toric aspheres. At 55°, the output beam is parallel to the input beam.

3.2 LASER BEAM DIRECTOR

If we confine ourselves to monochromatic light, then perfect reconstruction of a stepped wavefront can be obtained at the eigenangles which are determined by the grating equation. By scanning with an ABS unit, a discrete set of (two-dimensional) eigenangles can be addressed. This concept can be used as the basis of a laser beam director. The unit cell of an monochromatic afocal design is given on Figure 13a with the calculated point-spread function shown in Figure 13b which is based on a 9 $\times$ 9 elements microlens multiaperture ensemble.

3.3 INTEGRATED FOCAL PLANE

Several advanced technology sensor development programs currently under development at Lockheed identified the need to research innovative methods to achieve high-performance integrated focal planes. The utilization of a microlens-integrated detector has several potential benefits. MOT has been identified as a key technology to achieve the severe performance requirements derived from systems engineering flowdown studies.

Microlenses integrated with the detectors shown in Figure 14 will focus the incident energy onto each detector which can be significantly smaller than the pixel area. This has several benefits, including increased R_0A with subsequent lower thermal noise (thus increased sensitivity), smaller detector volume that will minimize the gamma susceptibility, and a relatively large available chip real estate area for other planar devices, such as multiple detectors for inband multicolor separation or for analog signal-processing devices. The use of a microlens also will allow near 100% fill factor to be maintained while allowing the readout under each detector to take full advantage of the total pixel area. The design may be a hybrid with an indium bump (Figure 15) or monolithically integrated MQW detectors where the available area may utilize readout electronics directly integrated with the substrate.

3.3.1 Focal Plane Array Microlens Hybrid

The FPA microlens hybrid concept is illustrated in Figure 15 which shows three layers of hybrid assembly. The backside illuminated detector arrays are initially built using conventional techniques. The substrates are thinned to the required thickness defined by system design and the microlens array is then fabricated by conventional photolithographic procedures. Fresnel-type microlenses were produced by binary fabrication processes on a CdTe substrate. The fabrication processes were pioneered by Lockheed R&DD in the initial phase of the Long-Wavelength Advanced Technology Seeker (LATS) program. A Fresnel-type microlens fabricated with a three-mask (eight-level) binary method is shown in Figure 16. A technology transfer agreement with LORAL for integrated detector development is currently underway. The hexagonal pixel topology is required from the system optimization point of view and is being implemented by LORAL on the focal plane to be delivered to the LATS program.

3.3.2 Inband Multicolor Detector Focal Plane (Dispersive Microlens)

Conceptual design studies for an advanced technology compact and lightweight sensor concluded that an integrated solid state solution to measure target spectral signatures is one of the most important potential methods for realtime technique in discrimination among various targets. Such an advanced sensor system requires an optical design that allows a simultaneous spectrally narrowband signal detection. Several techniques have been investigated in system engineering studies and one of the most technically innovative concepts relies on the dispersive microlens concept.[8]

The incident wideband wavefront contains temperature information about the targets and it is desirable to separate the wideband information to narrower subbands while maintaining perfect spatial and temporal registration. A successfully implemented optical design for the sensor would eliminate the need for extensive additional computational signal processing.

Micro-optics technology offers a potential solution through use of the dispersive microlens. We have been investigating a novel concept which may be implemented by superimposing the microlenses with a diffraction grating in each unit cell to cause the colors in the signal to be separated by the detector. The optical blur spot is stretched along an optical axis perpendicular to the superimposed grating direction. The dispersive patterns can be integrated into a combined surface fabricated as one surface utilizing photolithographic methods.

The dispersive microlens can be designed as either a Fresnel or non-Fresnel type. We are developing these two basic design options with both binary and our analog grayscale photolithography utilizing differential ion milling techniques.

The two basic concepts are shown in Figure 17: a dispersive Fresnel design (Figure 17a) and a dispersive non-Fresnel (analog) design (Figure 17b). Amber Engineering is assisting LMSC with the readout electronics for the Fresnel design option and we are jointly developing the non-Fresnel design and grayscale photolithography with Philips U.K. Computer-simulated unit cells for these two design are given in Figure 18 and fabricated test pixels for these two options are shown in Figure 19.

4.0 SUMMARY

We have discussed our current approach to micro-optics technology at Lockheed R&DD and outlined many of the system applications we have considered for advanced technology seekers. Micro-optics technology has a vast potential for making seeker components lighter, more compact, and more effective. It does this in three ways. The first is by combining bulky trains of optical elements into single elements through the use of hybrid optics (e.g., aberration correction).

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8. Gal, G., "Dispersive Microlens," under patent application, 1992.

The second is by introducing novel designs to achieve results previously obtained with macro-optics (e.g., beam steering/scanning). The third is by integrating micro-optical components with signal-processing elements to enhance information processing (e.g., multicolor focal planes).

Our efforts in micro-optics technology development cover all aspects of the technology, including development of analytic methods and computer codes, new fabrication techniques (e.g., fabrication in CdTe, grayscale technology), and laboratory testing. The general technology we have developed can be applied not only to the evolution of advanced seekers, but also to an entire range of areas, including optical communications, microlasers, and optical computing.

ACKNOWLEDGMENTS

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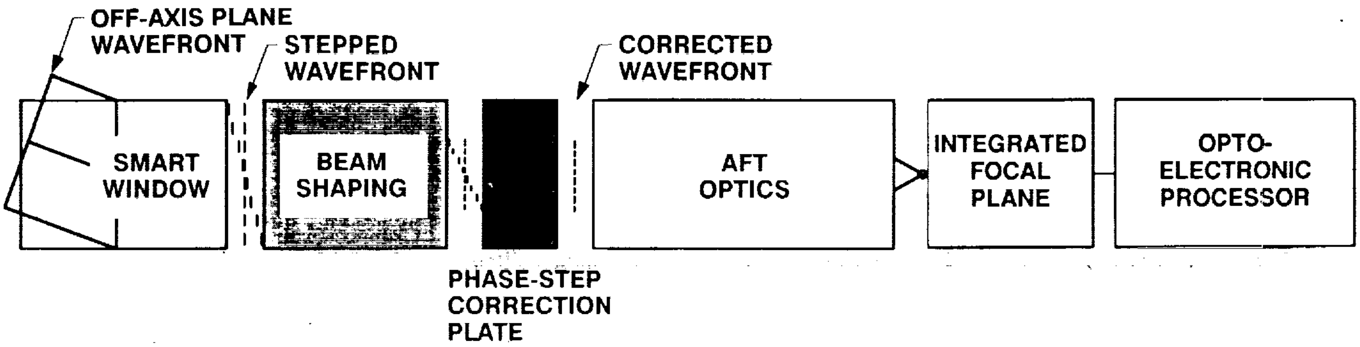


FIGURE 1. BLOCK DIAGRAM FOR A GENERIC PHOTONIC-Z TECHNOLOGY SMART SENSOR.

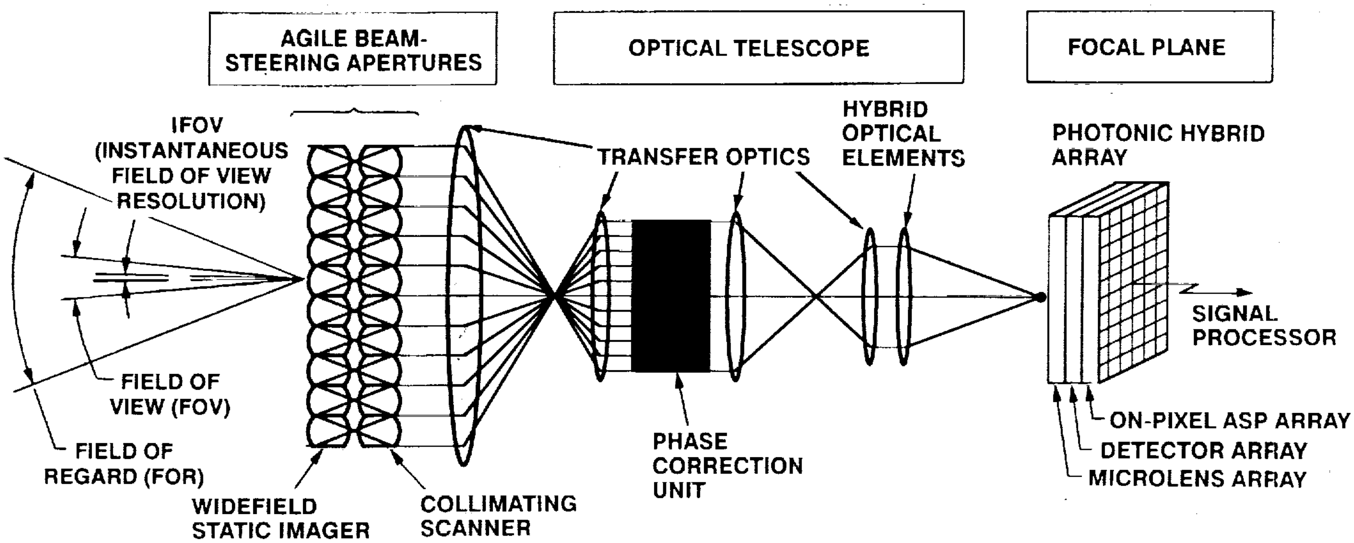


FIGURE 2. MONOLITHIC INTEGRATION WITH MICRO-OPTICS TECHNOLOGY.

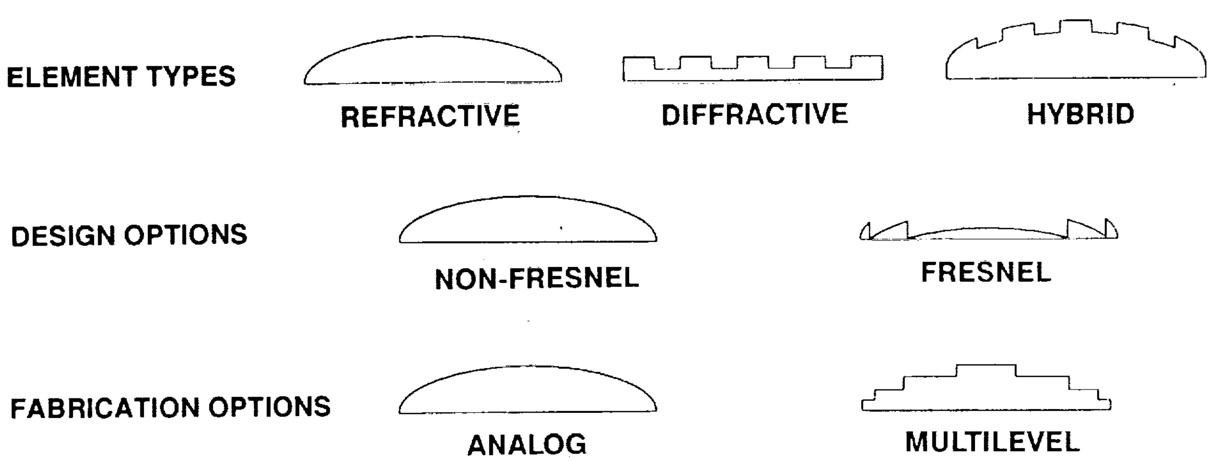


FIGURE 3. DIFFERENT MICRO-OPTICS OPTIONS (REFRACTIVE, DIFFRACTIVE, HYBRID) AND TYPES (NON-FRESNEL/FRESNEL, ANALOG/MULTILEVEL).

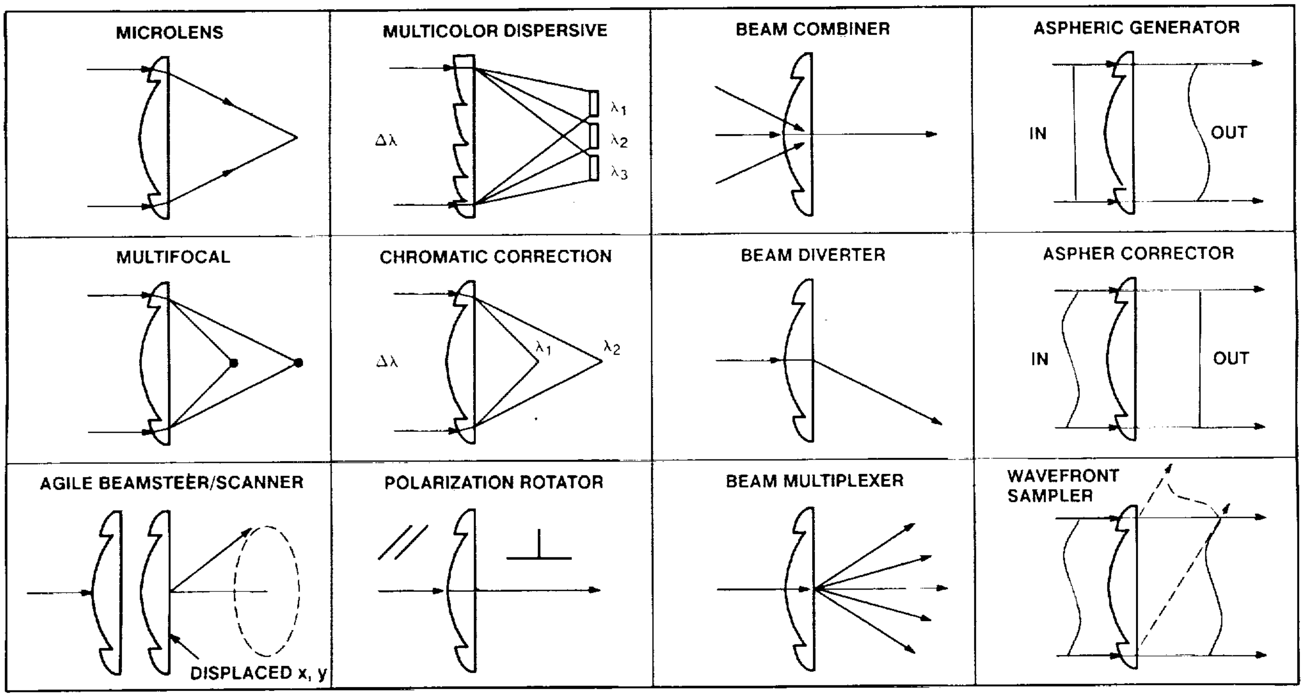


FIGURE 4. EXAMPLES OF MICRO-OPTICAL COMPONENTS.

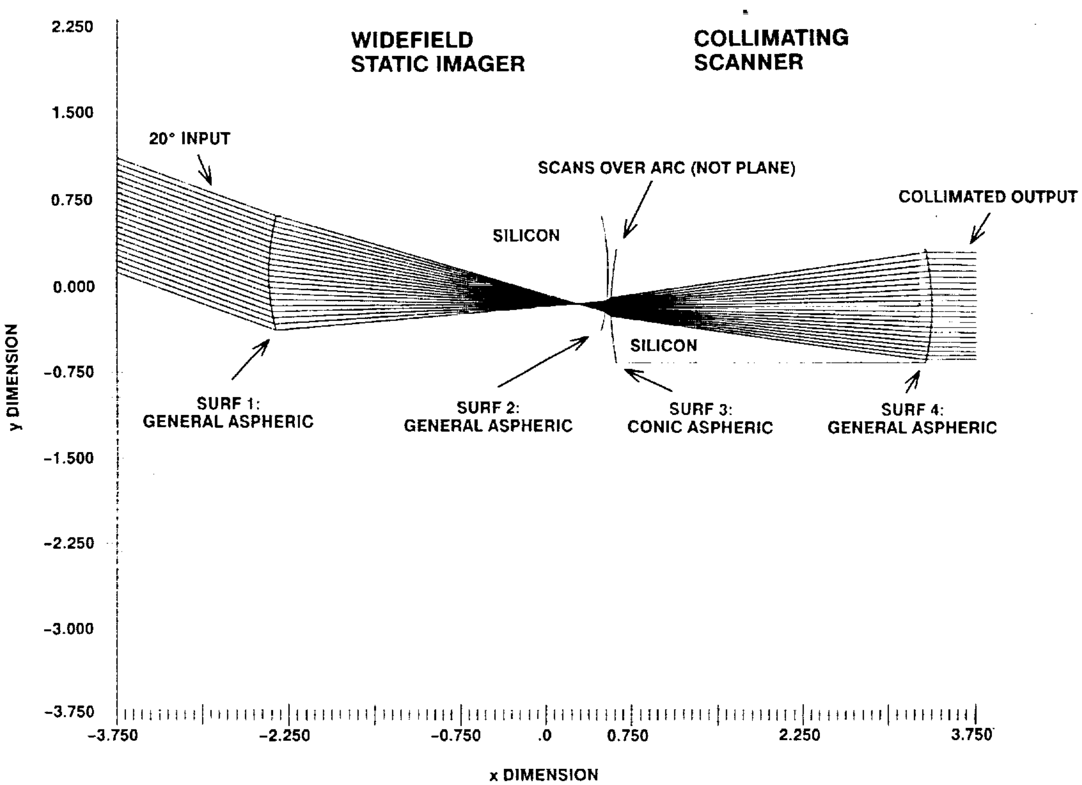


FIGURE 5. MICRO-OPTICS TWO-ELEMENT −1 MAGNIFICATION UNIT CELL TRAIN DESIGN EXAMPLE FOR AGILE BEAM STEERING. Collimating scanner is at the +20° scan position.

PHASE PLATE

FOCAL PLANE INTENSITY

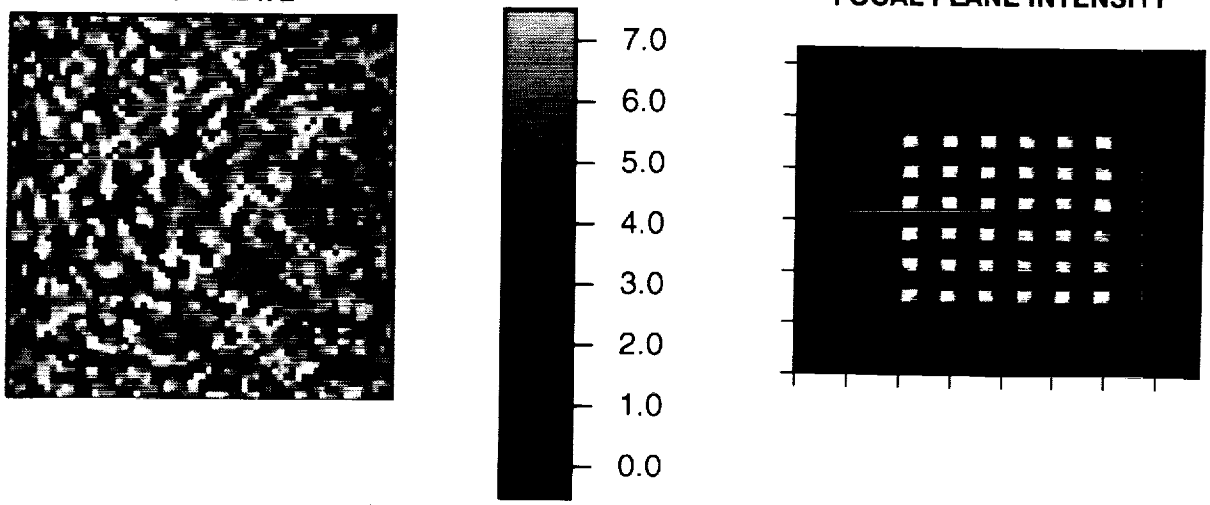


FIGURE 6. A 6 × 6 SPOT ARRAY PHASE PLATE GENERATOR AND THE RESULTING INTENSITY DISTRIBUTION.

REACTIVE ION ETCHING– SILICON ARRAY

ION MILLING–CdTe ARRAY SQUARE PIXELS

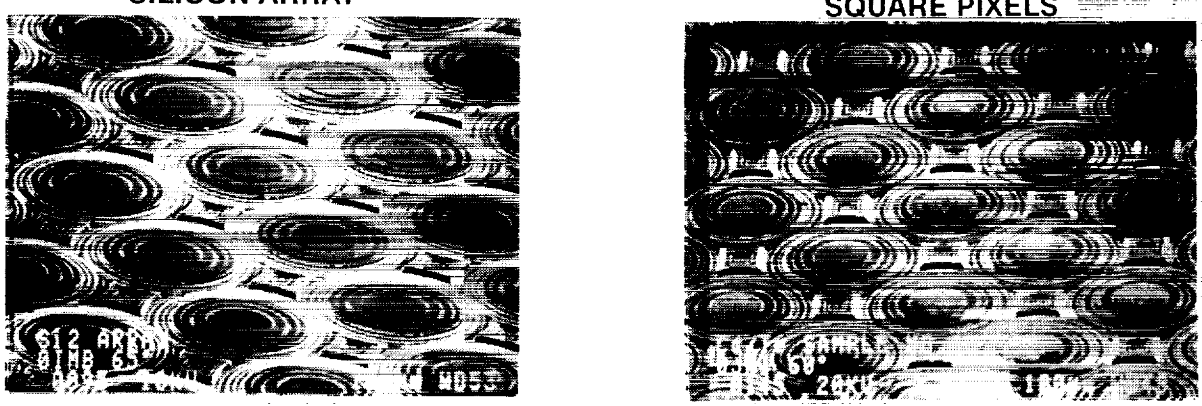


FIGURE 7. EXAMPLES OF THREE-MASK, EIGHT-LEVEL MULTILEVEL FRESNEL MICROLENSES OPERATING IN THE LWIR WAVEBAND REGION.

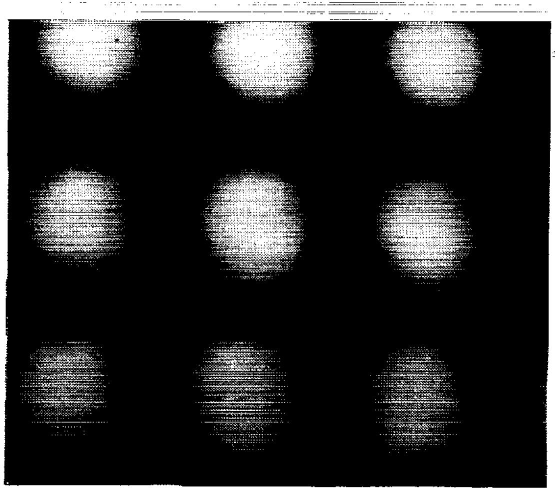


FIGURE 8. MICROLENS FABRICATED WITH THE GRAYSCALE PROCESS.

MICROCOOLING CHANNELS

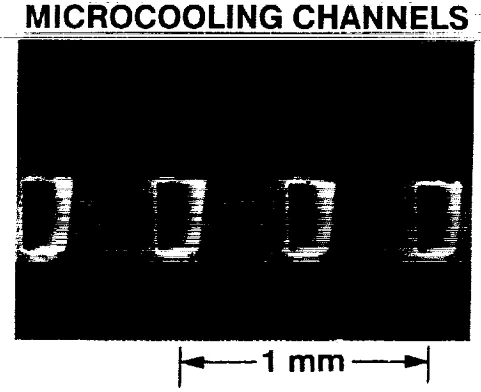
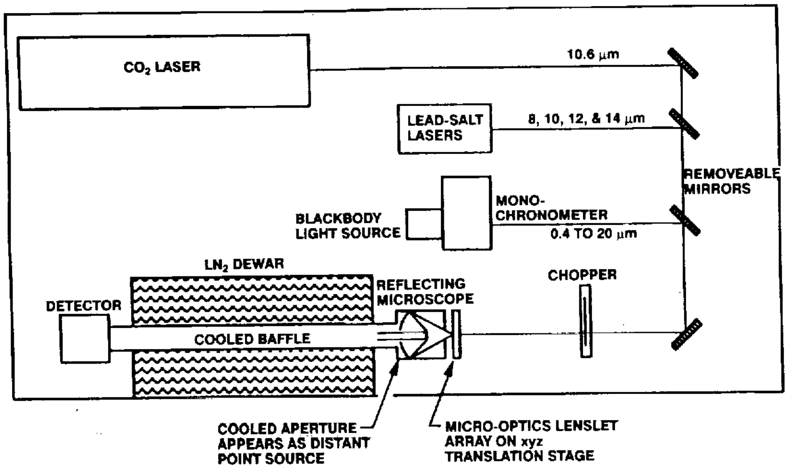
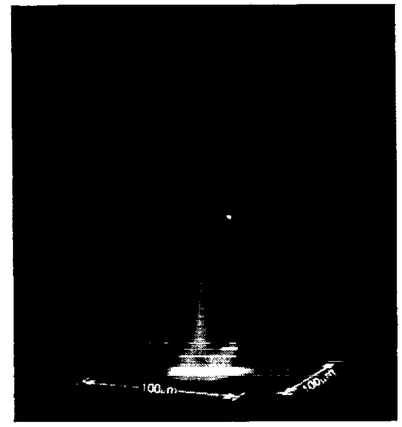


FIGURE 9. EXAMPLE FOR MICROCHANNEL FABRICATED WITH A HOT KOH ETCH IN Si.

Top part of channel is closed by fusion bonding to a separate Si wafer.



a. OPTICAL BENCH LAYOUT



b. MEASURED PSD FOR A SINGLE MICROLENS SHOWN IN FIG. 7

FIGURE 10. MICROLENS PERFORMANCE TEST.

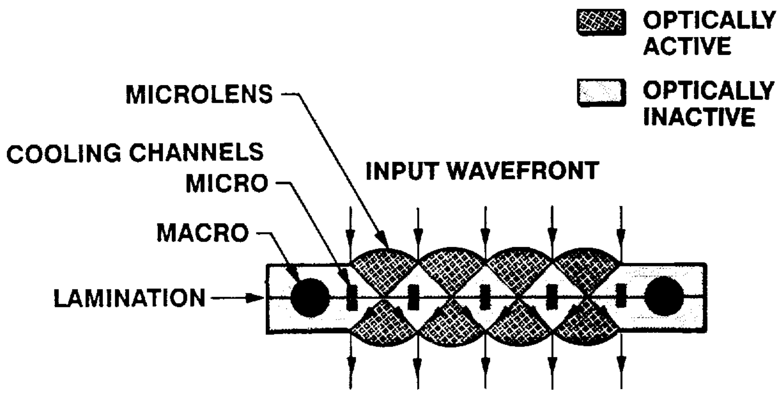
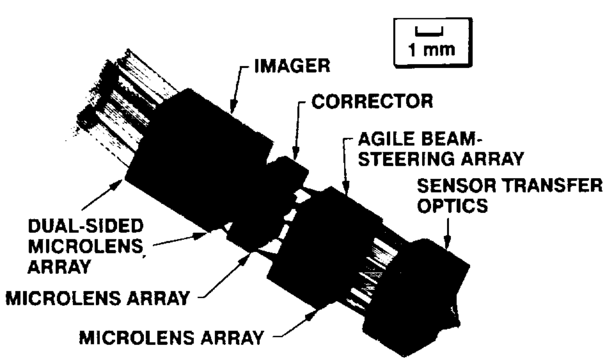
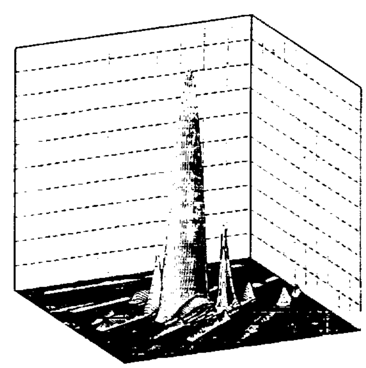


FIGURE 11. USE OF MICROLENS ARRAY AT THE APERTURE CREATES OPTICALLY INACTIVE VOLUME FOR MICROCHANNELS FOR INTERNAL COOLING.

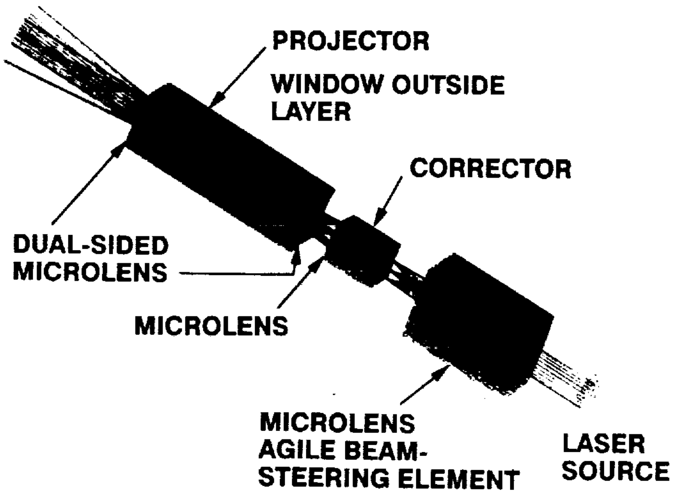


a. 3 × 3 ELEMENT SEGMENT OF THE ABS UNIT

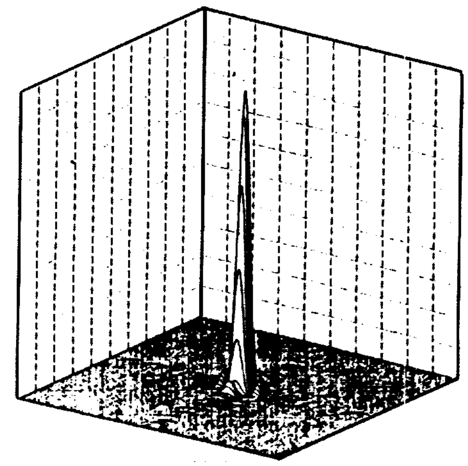


b. UNCORRECTED POINT-SPREAD FUNCTION FOR A 9 × 9 ELEMENT SEGMENT AT THE UNSCANNED POSITION

FIGURE 12. DESIGN EXAMPLE FOR A POLYCHROMATIC PHASED-ARRAY WINDOW OPERATING IN THE MWIR WAVEBAND REGION.



a. UNIT CELL OF A LASER BEAM DIRECTOR



b. POINT-SPREAD FUNCTION OF A 9 × 9 ELEMENT PHASED-ARRAY APERTURE AT EIGENANGLE SCANNED POSITION

FIGURE 13. EXAMPLE FOR A MONOCHROMATIC ABS DESIGN.

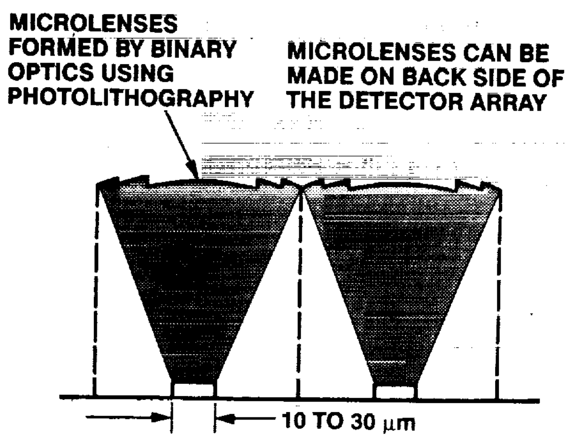


FIGURE 14. CONCEPT OF MICROLENS INTEGRATED WITH A DETECTOR.

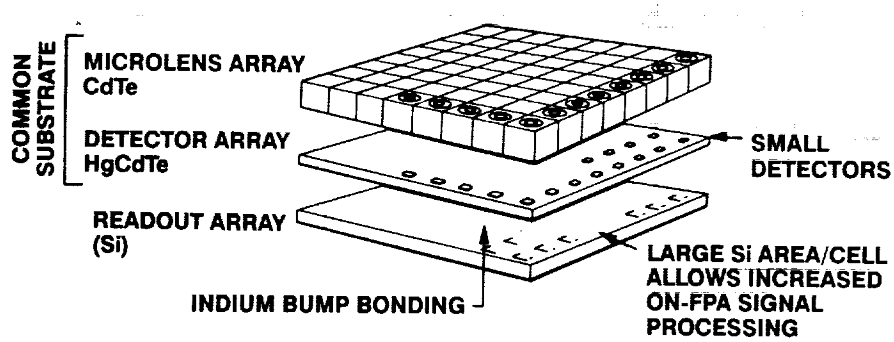


FIGURE 15. PHOTONIC HYBRID ARRAY FOR LWIR HIGH-PERFORMANCE FOCAL PLANE.

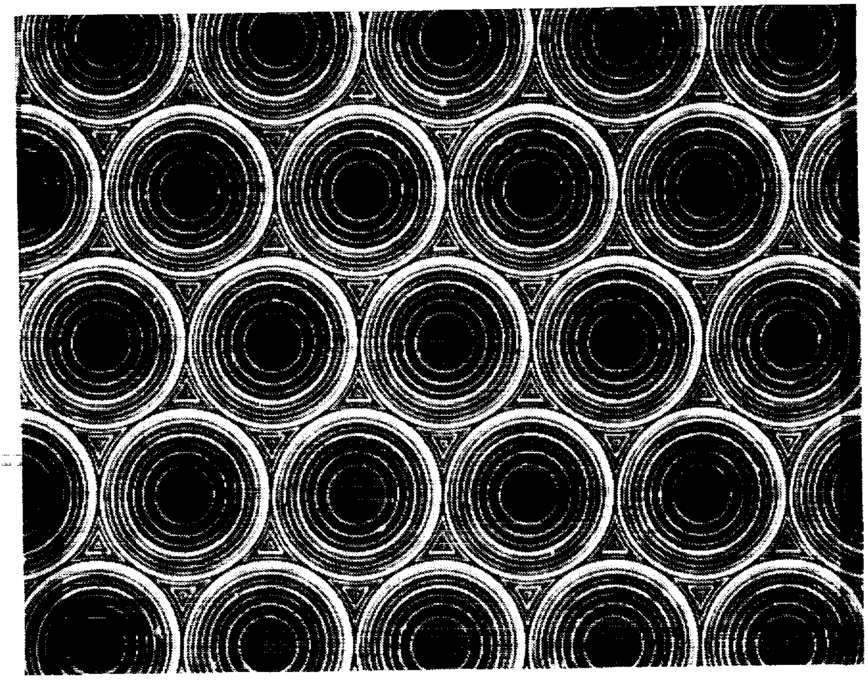
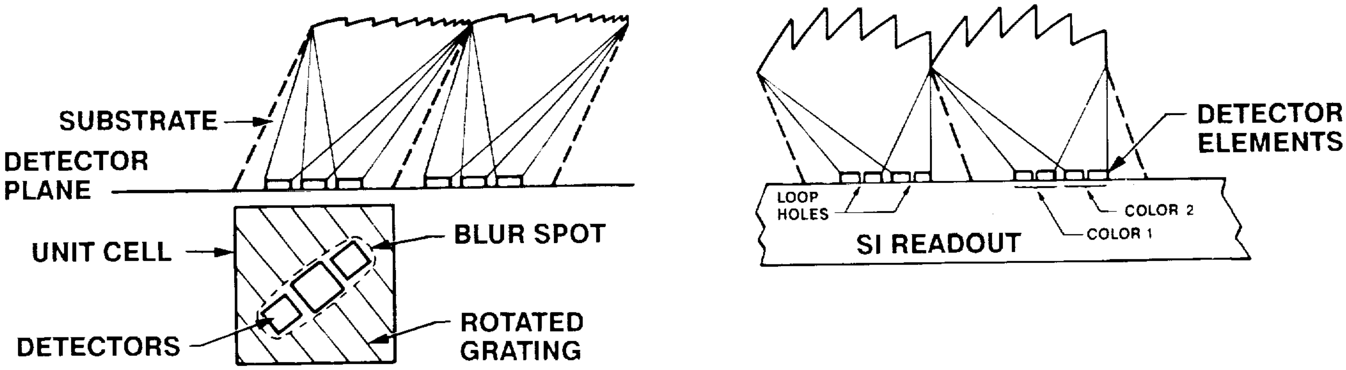


FIGURE 16. CdTe MICROLENS ARRAY WITH HEXAGONAL PIXEL LAYOUT FOR LWIR OPERATION.



a. DISPERSIVE DIFFRACTIVE

b. DISPERSIVE REFRACTIVE

FIGURE 17. DISPERSIVE MICROLENS CONCEPT.

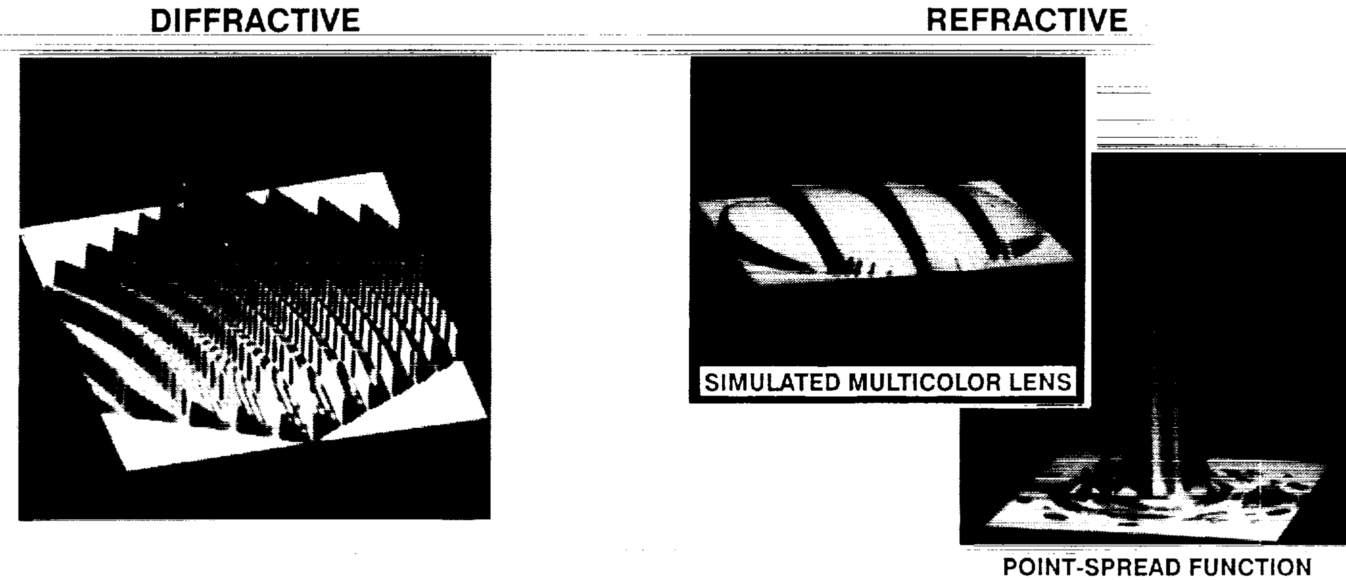
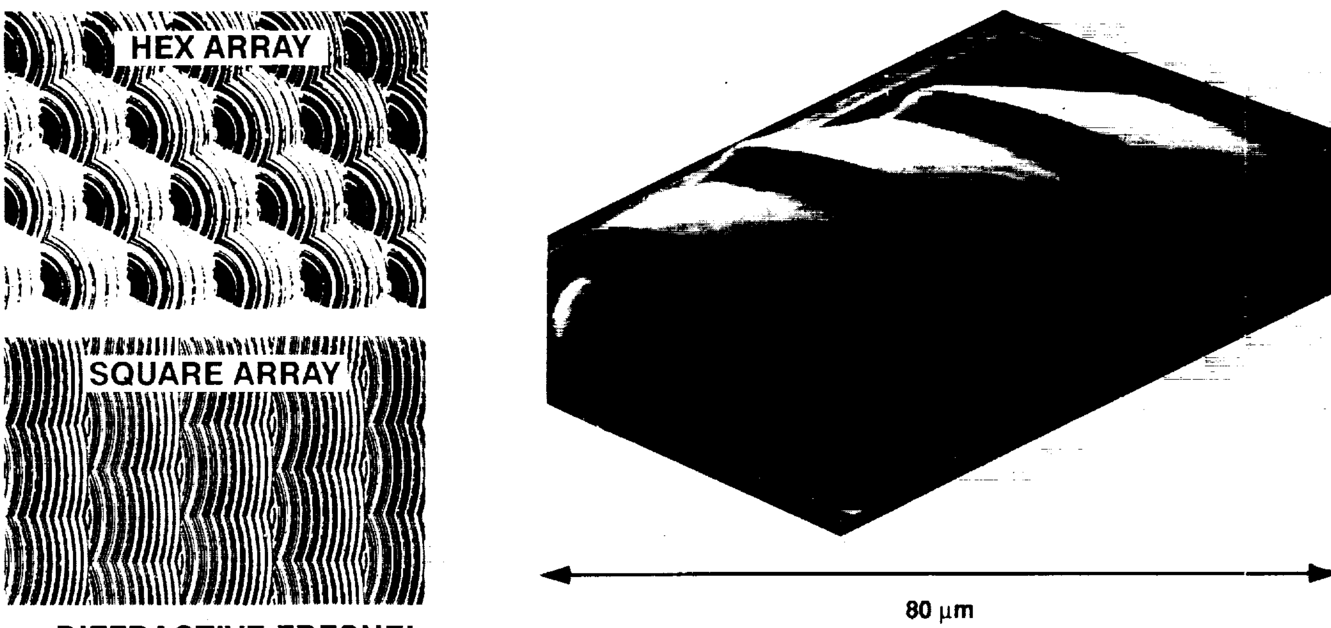


FIGURE 18. SIMULATION OF DISPERSIVE MICROLENSES AND PREDICTED OUTPUT.



a. DIFFRACTIVE FRESNEL TYPE WITH BINARY METHODS

b. REFRACTIVE TYPE WITH GRAYSCALE MASK

FIGURE 19. FABRICATED DISPERSIVE MICROLENSES.