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OVERVIEW OF MICROOPTICS: PAST, PRESENT, AND FUTURE

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ABSTRACT

Through advances in semiconductor miniaturization technology, microrelief patterns, with characteristic dimensions as small as the wavelength of light, can now be mass reproduced to form high-quality and low-cost optical components. In a unique example of technology transfer, from electronics to optics, this capability is allowing optics designers to create innovative optical components that promise to solve key problems in optical sensors, optical communication channels, and optical processors.

1. INTRODUCTION

Many of the current micro structures in optics are based on binary optics technology. This is an inherently diffractive optics technology that uses computer-generated designs of microscopic relief patterns and electronic circuit etching technology to create novel optical devices and to provide design freedom and new materials choices for conventional refractive optical elements. Over the past ten to twelve years we in the holographic optics community have learned to produce diffractive and mixed refractive-diffractive devices that are highly efficient and of high enough quality to be used in cameras and in medical applications. These devices are fabricated by methods compatible with current lithographic and integrated circuit techniques.

In the early seventies, the Defense Advanced Research Projects Agency (DARPA), the Air Force, and many industrial groups started to drive electronic circuit features to below the one-micron level. This effort led DARPA and the National Science Foundation (NSF) to establish a MOSIS (Metal Oxide on Silicon Integrated Systems) foundry service in 1981. MOSIS aggregates designs from different sources onto one mask set; instead of paying $60,000 for a dedicated set of masks and a fabrication run, users can get packaged parts for as low as a few hundred dollars. This service dramatically lowers the risk of electronic circuit prototyping. In the late seventies a micromechanics technology piggybacked on the VLSI and VHISIC electronics technologies to develop micromotors, microaccelerometers, microchromatometers and other mechanical devices made by computer lithography and etching technology. Now we see the integration of processing electronics and microsensors and actuators on a common silicon wafer and chips.

Similarly, in the mid eighties, with the support of Jasper Lupo, DARPA started a program called Binary Optics. The goal was to piggyback a new diffractive optics technology on the flourishing micromachining technology with the participation of federal laboratories, universities, and industry. DARPA's programmatic goals then were three-fold:

(1) Develop an optics technology based on electronic circuit fabrication technology for the purpose of cost and labor savings in military sensor systems, for creating new freedom in designs and materials, and for developing new composite optical functions that could not be created with the current technology,

(2) promote computer-aided design of total electrooptical systems, and

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(3) launch a broad-based diffractive optics technology in U.S. industry.

Therefore, the key features of the microoptics technology that evolved since1984 were:

(1) That it dealt with one of the three ways of manipulating light -- diffraction. Refraction and reflection are the other two. Soon after the startup of the program, diffraction was blended with the other two ways in order to cover broad waveband applications and a mixed macro technology emerged.

(2) That fabrication be based on holography microlithography, and ion-etching technology.

(3) That the new technology provide design freedom and materials choices in imaging sensors by diffractively compensating the dispersive properties of infrared, visible, and ultraviolet materials.

(4) That the arrayed micro components shape, steer, filter, and process light in new ways to produce smart sensors that would be adaptive and agile.

2. THE PAST: LARGE FEATURE APPLICATIONS

In the early days of the binary optics program diffractive optics work proceeded along two approaches. The first was based on planar structures only, where all the optical power was diffractive. It required very high resolution lithography and a full electromagnetic field treatment of the optics in order to describe the efficiency characteristics of the devices accurately (1). These planar devices generally were sensitive to the polarization of the incident fields and were useful only for narrow optical bandwidths and fields-of-view. Later, techniques were developed to circumvent most of these limitations by trading structure depths for lower periodicities and less diffractive power. In other words, quasi planar structures were fabricated where the etch depths were multiple wavelengths deep, and that had characteristics of both refractive and diffractive microoptics. A true Euglina of the refractive and diffractive microoptics fields evolved naturally.

The second approach was based on mixing refractive with diffractive power on macro elements, typically on fast lenses. With mixed optics a spherical surface provides the raw focal power, and the diffractive micro structure corrects the spheric and chromatic aberrations of the element. For such applications one needed only low resolution, and more importantly, low accuracy lithography (generally one-micron accuracy was good enough). Because of the coarse features of the diffractive patterns, the devices generally exhibited little sensitivity to polarization and could be used with wide optical bandwidths and in large field-of-view applications, from infrared to deep ultraviolet wavelengths (2).

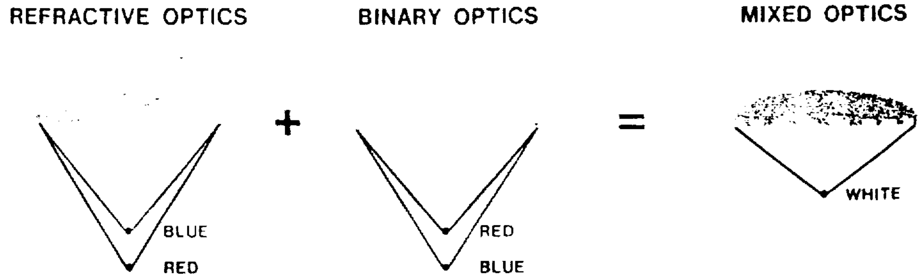

Figure 1. Chromatic Aberration Correction With Binary Optics

From another perspective, mixed refractive and diffractive optics fulfill an alternate complementary role, for not only can diffractive optics be used to fine tune the surface profile of spherical elements and eliminate spherical aberrations, it can also modify the bulk properties of optical materials. The dispersive quality (change of refractive index with wavelength) of all optical materials is a consequence of light absorption in a material as a function of wavelength. Conventional optical designs compensate for dispersive or chromatic aberrations by cementing together different materials with carefully varied radii to produce compensating dispersion characteristics. These lenses need not have dispersions of opposite slope; a mere difference in refractive index is sufficient to null chromatic aberration over a finite bandwidth. Similarly, with binary optics, we can achieve an achromatic balance between a dispersive lens material and a diffractive pattern etched into the surface of that material. Such a binary optics element is an advanced implementation of a highly efficient Fresnel zone pattern in which phase gratings are used to focus light into a corrected spot (see Figure 1).

As a grating, a binary optics element has inherent optical dispersion properties that can be tailored by varying the geometric dimensions of the zone rings in a space-variant manner, i.e., ring widths, depths and spacings, irrespective of the intrinsic properties of the substrate material. The selectable dispersion characteristic can be used to achromatize optical materials over a wide bandwidth. The high efficiency (no undesired scatter) determines the effectiveness of this kind of compensation. In general the diffractive features are much larger than the used wavelength, whereas pattern accuracy must be comparable to the wavelength; in complex system designs the number of needed elements can be cut in half by use of binary optics. Micro machined optical elements can have dramatically improved resolving power and useful bandwidths, as is demonstrated in Figure 2 for a range of wavelengths and lens speeds.

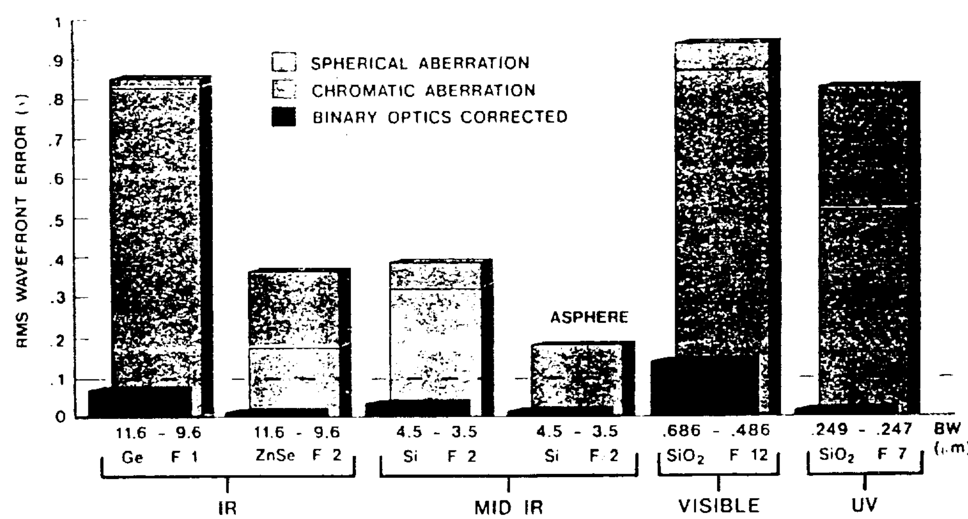

Figure 2. Diffractive Correction of Various Lenses in Four Wavebands

Many companies are now routinely using micro machined and mixed elements in the design of new optical systems. Hughes, Loral, Honeywell, Optical Filter, Rockwell, Texas Instruments, 3M, Polaroid, and many others are active in the field.

As a result of the modest DARPA program that began in 1984, a truly enabling optics technology has evolved . The first generation of the micro optics technology (aberration correction of conventional optics) has been transferred from a federal laboratory to more than fifty companies and has spawned six U.S. startup companies (see Figure 3). Four years ago we moved in earnest into the second generation of novel devices: arrayed microoptical elements.

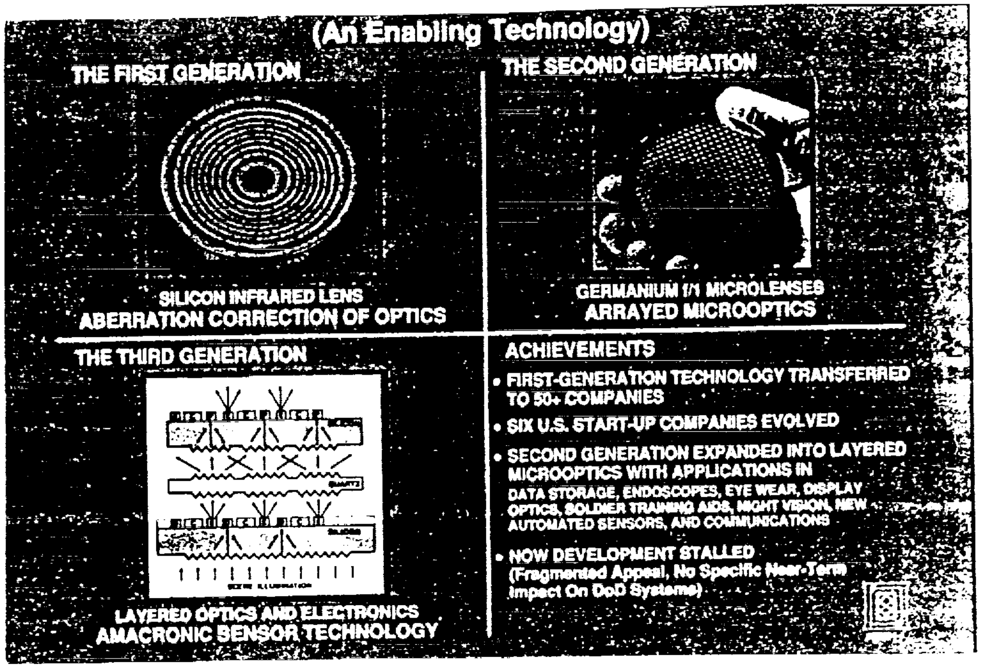

Figure 3. Three Developmental Generations of the Microoptics Technology

3. THE PRESENT: LARGE ARRAYS OF FAST MICROOPTICS

Much of the current research activity centers on the fabrication of microfine arrayed optics. One of the many unique applications of binary optics is microoptics, a technology that produces optical elements such as lenses, multiplexers, and filters that range in diameter from a few tens of microns to one millimeter. The lithographic flexibility in layout and design of the arrays with rectangular, round, or hexagonal close-packed layouts (while maintaining optical coherence over the array) makes this technology unique among all other current fabrication techniques. The optical phase profile of a lenslet, for example, is not restricted by fabrication constraints either; designers can choose optimal surface profiles such as spheric, parabolic, aspheric, astigmatic, and anamorphic, depending on application requirements (3,4).

The use of microoptics in systems is still new, and occurs primarily in laser diode beam shaping, on-chip optical tasks, focal plane imaging, and processing functions. Binary optics with 0.1 micron accuracy and 0.5 micron resolution has been used to demonstrate coherent lenslet arrays of 20,000 elements/cm^2, f/1 speed, and zero dead spacing (optically inactive areas between the lenses). An individual element can exhibit root-mean-square wavefront errors limited to $\lambda/50$ and strehl ratios of 0.98 (the strehl ratio is defined as the peak field amplitude in the focus normalized to the diffraction-limited amplitude). In other words, with binary optics and very-large-scale integrated step-and-repeat technology, large arrays of micro lenslets can exhibit full diffraction-limited performance. Because this is an inherently planar optics technology, very large segmented apertures can be assembled in etched dielectrics or metals or embossed in plastic-like materials. Current research centers on extending this microlens technology to broad-waveband (more than 20% fractional bandwidth) applications by deep-etch structuring or by blending refractive and diffractive microoptics on either side of a substrate.

The unique capability of current microoptics technology can be demonstrated by three key example applications to optical imaging sensor systems. These applications were chosen because of our specific interest in optical sensor technology. Throughout the conference we have heard from other organizations about their applications, ranging from optical communications, optical data processing, and data storage to medical implantation devices. Although the current work in microoptics is primarily an enabling technology development, the very nature of an enabling technology means that its success can only be measured in terms of useful applications in many fields, and transcends applications in specific devices.

Our first important application exploiting microoptics technology in sensor systems is with agile and high-speed steering of images and laser beams. The lack of an agile steering element is the Achilles heel of most electrooptical sensor systems. A possible solution uses layers of coherently arrayed afocal microoptics that is moved via piezo or electrostrictive forces to form a programmable beam scanner with a minimum amount of motion (half a lens diameter maximum). Alternatively, layers of confocal microoptics with electrooptic material sandwiched in between can be used to form the optical equivalent of a phased arrayed antenna with high speed steering properties so well known by the radar community.

The second class of applications that has our long-term interest is the formation of arrayed microcavities for one and two dimensional arrays of solid state lasers. These arrays can form extremely bright laser sources by coherently adding the power of the elements in the array. Radiation power densities of today's single diode lasers already exceed those at the surface of the sun, and materials limitations prevent further increases in laser power density. Yet, the very small radiation area of a single laser can reliably produce only about 50 mW. Only coherent addition of sparsely spaced lasers in an array can overcome the thermodynamic barrier to higher laser diode power. Figure 4 shows a collection of six tested microcavity designs using microoptical multiplexers, filters, phase converters, fractional Talbot gratings, and interlaced microelements (5). Some of the elements require interlaced refractive and reflective lens arrays and coherently integrated components on both sides of an optical substrate.

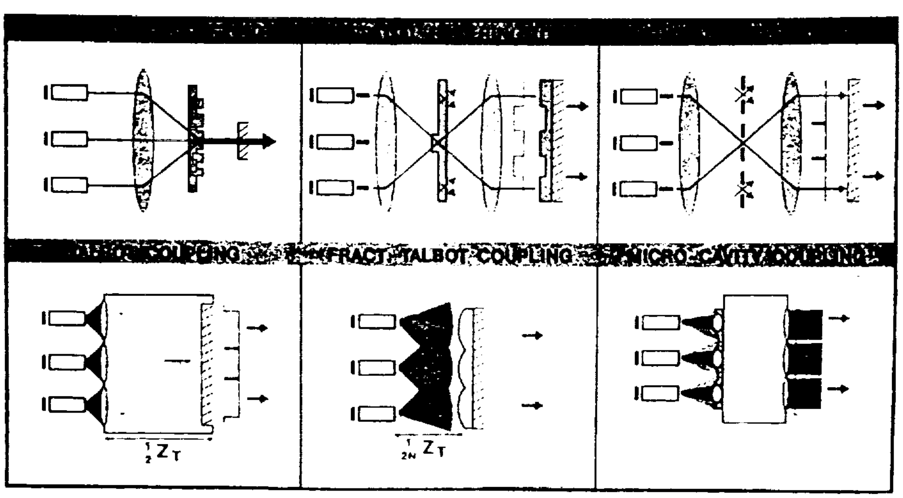

Figure 4. Various Tested Microcavity Designs for Coherent Laser Array Addition

The binary optic elements couple, lock, and control modes of a new generation of coupled-laser microcavities, and the technology will radically change the capabilities of all active optical sensors probably with as much impact as magnetrons had on radars. In less than ten years, square-inch-size power sources producing a hundred watts of coherent laser power will be a reality.

A third and broad class of problems requiring optical microcomponents is in mapping and transforming optical field distributions into a new distribution. During the conference we heard about examples of spatially matched filters for target and fingerprint identification (6), about filters that map cartesian into polar coordinates (Mellin transforms), and about composite matched filters for preprocessing imagery. All these applications have been demonstrated with binary optical components. However, the first generation of mapping devices only requires one planar surface to phase and direct the light. Current research work centers on mapping arbitrary distributions of light into a new one with the minimum number of surfaces and maximum light throughput efficiency. A good demonstration of this technology is the geometric transformer for end-pumping solid state lasers shown in Figure 5. Microoptics aligned on two sides of a bulk substrate maps a linearly segmented array of laser pump diodes into a uniformly filled aperture that is mode matched to a solid state YAG laser rod for maximum pump efficiency. Such a transformer requires a space-variant off-axis microlens array to redirect the light filling the back-plane exit aperture uniformly and a space variant phase corrector to match the mode of the laser cavity.

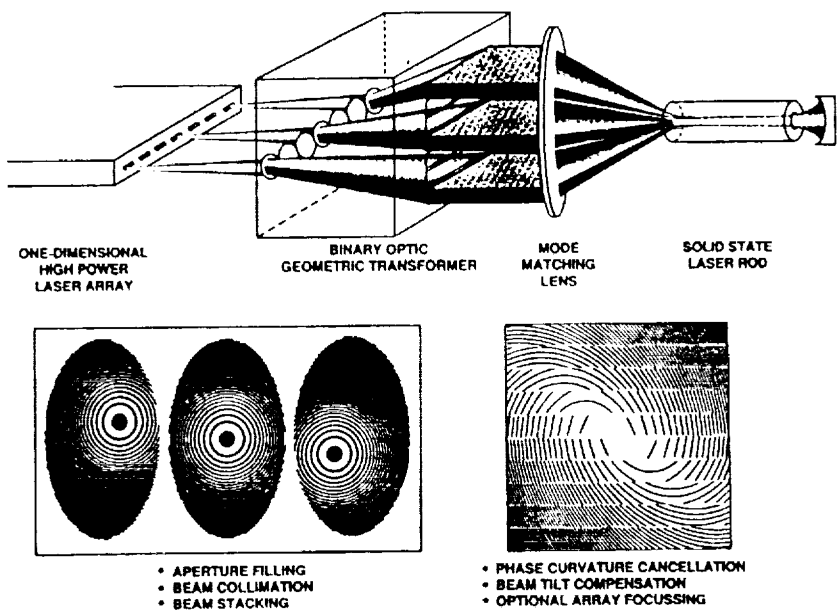

Figure 5. Optical Transformer for End-pumping of Solid-state Lasers

These are only a few examples of the blossoming microoptics technology. Does this mean the road is clear for far more complicated devices? Clearly not: there remain many unsolved technology problems that are impeding broader use of this technology. Let me mention a few. Current support of software for workstations and displays that is adapted for diffractive microstructures is virtually non-existent. Ray-trace programs need to be more consumer friendly for people working in diffractive optics and must be matched to drivers that can write data blocks in polar coordinates. Although mask foundries are now widely used for binary optics mask production, the software that drives the pattern generators or e-beam machines is cumbersome and geared to the cartesian coordinate systems used in the electronics industry. Mebes machine language needs to be developed to satisfy the needs of optics applications. In terms of device fabrication infrastructure are DARPA supported microoptics MOSIS fabrication foundries on the horizon to drive down the cost and broaden the acceptance of this technology? We also still have a lot to learn about the problems that make microoptics fabrication different from micromechanics and micro electronics. For example, the technology for etching large-area deep-structures (more than 2Π deep) and replanarizing the different lithographic layers is still unchartered territory. Dual-sided lithography and layering of the micro optics on different substrate with sub-micron precision has still not been mastered either.

4. THE FUTURE: MIXING ELECTRONICS, OPTICS, AND MECHANICAL STRUCURES

As microoptics technology matures, we shall see develop a dual role for optics in imaging sensors. Not only is optics required in photon collection processes such as image magnification, agile image scanning, and the segmentation of foveal and peripheral vision or of colors, but optics will play an important role in shaping detection architectures and image preprocessors as well. These high-throughput processing roles may come in the form of optical communication between layered processing wafers, as cross-coupling neighborhoods of clustered detector arrays, and as inter-wafer resonant processing architectures that group moving centroids and segmented texture clusters in robotic vision applications.

Present-day electronic imaging sensors are asked to perform a wide variety of functions, often with contradictory requirements in tracking, surveillance, identification, clutter rejection, or in extraction of textured patterns. But, the image-in/picture-out approach of the past in automated recognition systems is fundamentally flawed. These sensors have evolved from a camera technology developed at the turn of the century and are based on photographic or electronic recording of 2-D images that are presented to the human eye. All post processing then centers on extracting and enhancing detected features in a serially processed single image. This approach leads to very large and high speed computer system requirements.

Systems that can adapt processing architectures or interact with a changing environment do not yet exist. However, most optical sensors in nature did develop complex eye adaptability by necessity for survival. For example, whereas vertebrates have mostly simple or camera eyes, the human corneal type imaging is uncommon outside the land vertebrates. The only other large group with corneal eyes is spiders. Insects have mostly compound eyes, or sometimes their larvae are born with corneal eyes that are discarded as they grow and are replaced by compound eyes. Among the marine mollusks and crustations the most interesting eyes are found (due to photon starvation). Many of the crustation eyes are based on mirrors. Scallops have concave mirrors, others have convex lenses and sometimes one large eye and one small one. Capepod crustations have roving fovea, a linear scanning retina (3x410 elements), and a field-of-view that is a linear strip, as in many of our infrared sensors (7). The variety in foreoptics is great, e.g., male pontella fish have three lenses (one parabola and two spherical lenses), the females have two lenses (one parabola and a spherical lens), but the variety in retinal preprocessing architectures is even greater, although far less understood. Besides simple registry of images, there are retinal processing cells which are particularly interested in movement, regardless of what is moving. It has been known for some years that, in the eyes of some creatures, there are cells which will respond to movement even at levels of light too low to cause them to fire for the illumination as such. For most mammals, this sensitivity to moving objects suits prey and predator functions. Work with rabbits and ground squirrels showed that not only frogs but mammals have specialized retinas. The squirrel is particularly fitted to detect the direction of motion of small objects (maybe that is why it freezes in on-coming car headlights). The rabbit has "fast" detectors and "slow " detectors far more sensitive than man's. Each of these optical sensors is tuned by evolution to fit a specific set of defense and predator requirements.

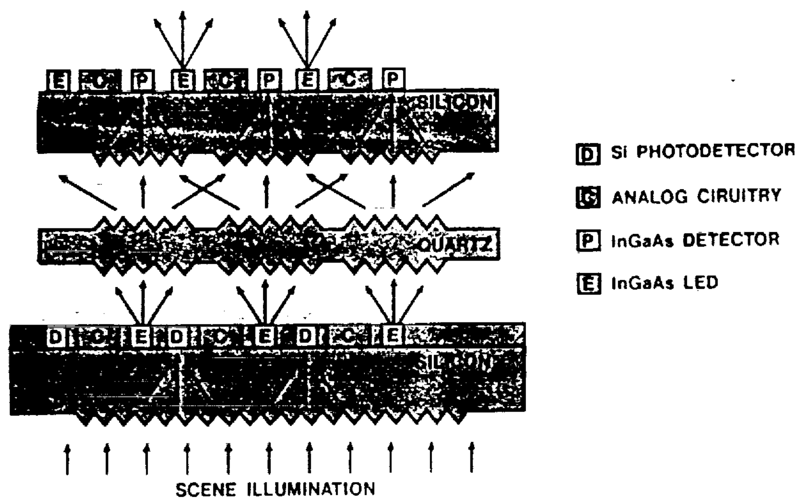

Figure 6. A Multilayer Amacronic Network with Microlenses and Micromultiplexers

Faced with such a wide ranging optical sensor complexity in nature, it is imperious to assume that our optical image-in/electronic image-out (the basis of all cameras) is not deficient for most tracking and recognition tasks. If we are to tackle one of the great remaining challenges in science, namely, robotic vision, we need to start developing focal plane processors for data rate reduction and develop sensor outputs that are fed back to the optical front end. The feedback would give the sensor agility and nonlinearity and would avoid the data overdose that always follows conventional maximum-resolution image-rastering strategies. The new approach will require compact optics and optics integration with focal plane designs (see Figure 6) The new microoptics technology based on lithography and holography can help significantly to provide agility feedback and a high throughput competitive non-linear preprocessing capability.

The first stage of the change in sensor technology requires replacement of detector arrays that consist of densely packed elements and leave no space for processing with integrated focal plane microlenses that concentrate light on smaller pixels and leave enough room for local electronic processing cells. Binary optics can focus pixel-sized signals to more efficient (lower noise) shrunken detectors and it can create sufficient space on the back focal plane to implement primary amacrine type networks and enough space to optically re-emit processed pixel information to the next processing layer. The second stage in amacronics development requires very low power circuitry to be interlaced with the detector grid and to process locally and couple electronically to the nearest detector neighbor. The most rudimentary electronic network can adapt images to changing light levels by space-variant gain settings and by amplifying differences between detectors and local averages. Neighborhood groupings then can compete and adapt away stationary or fixed patterns in space and time.

In the third stage of development each locally processed pixel output must be optically transmitted off the back focal plane to the next processing network level. The multitechnology integration of microoptics, detectors, analog circuitry, and microlasers in the form of LED's, quantum-well lasers or SEED devices, is very complex. However, the complexity appears necessary in order to handle the inherent high-throughput requirements of image processing.

The term "amacronics" was recently given to optically and competitively coupled focal plane structures with local electronic processing cells. Amacronics derives its name from the biological term for layered "a-macros" or "short-range" interacting networks observed in front of mammalian retinas. Key amacrine functions are motion detection, edge enhancement, and space-variant image dynamic range reduction. With an optically crosslinked detector array, competitive non-linear center-surround designs that form the basis of biological amacrine functions can be implemented. For a description of these micro-sized optical pixel multiplexers, see the paper by Wong in these conference proceedings (8).

Companies like Sony and Hitachi have begun to market the first stage of amacronics technology by integrating microoptics on the front focal plane and electronic processing modules on the free space created between CCD detector arrays. The result is that their cameras have less dark current, one extra f-stop in sensitivity, and a higher dynamic range with electronic shuttering and a reduced fixed-pattern-noise dependence.

5. SUMMARY

In this presentation I have reviewed two generations of macro- and microoptical structures, and, through examples of applications, may have given you a glimpse of what the future may hold for optical sensors that use the new enabling technologies. Clearly, that future is bright with wide ranging implications; however, I would like to make three observations.

The first is that the review I presented is myopic because of my heavy bias toward smart sensor and robotic vision development we in our research group at MIT Lincoln Laboratory are involved in. It is not representative of the true capabilities and the broad ranging applications of microoptics. The technology has as many applications in optical communications in space and in fibers, optical crossbar switching, fiber coupling, mode matching, and filtering. Alternatively, optical computing and high-throughput processing which generically is a quasi-monochromatic optics technology, will also greatly benefit from the flexibility and the microscopic nature of the technology. All these applications fall under the heading of photonics used to describe the sensor, communication, and data processing applications. Photonics has been described as a "critical emerging technology" by the National Research Council and in that context microoptics is seen as an enabling technology.

However, to gain broad acceptance by a systems community not intimately familiar with the microoptics capabilities, the photonics community must actively pursue applications outside the field of optics, for example, in medicine as interocular or corneal devices and as key endoscopic optics components and in miniaturized surgical tools. In the large data storage, retrieval, and printing domain, there are significant microoptics applications in optical disk readers, laser printers, and in optical storage devices. The widest market for microoptics certainly will be in the entertainment domain, where microoptics will be used in flat screen displays, HDTV, artificial reality, and 3-D perception applications (see Figure 7).

The second point has to do with the funding level of the new technology. Microoptics as an enabling technology development is not likely to be funded generously. Yet, it is a high technology field with severe requirements on capital investments in clean rooms, lithographic equipment, high-vacuum etchers, electron-beam writers, microscopes, etc. Governmental agency funding generally, and particularly nowadays, goes to near-term solutions of problems, not to future technology investments.

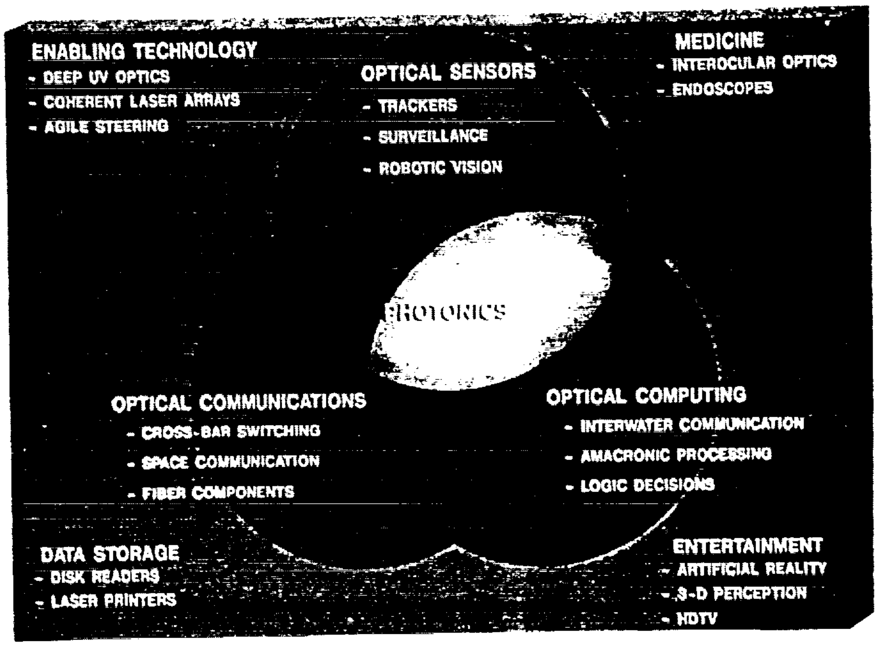

Figure 7. Multiple Binary Optics Application Domains

But microoptics won't be considered as a viable solution to a systems problem until the technology is better understood and further developed. So we must slowly bootstrap ourselves by continually proving the value of the technology with immediate applications. The past approach where passive components could be developed in isolation appears no longer feasible (except for niche applications). We in the microoptics community must cross the threshold into new multi-disciplinary technologies where we must mix optics with analog VLSI, neural network, non-linear material, microlaser, and other technologies. This will require us to forge collaboration with other disciplines in information processing, biology, medicine, data storage, and display fields.

The third and final observation is that the new optics technologies are at a historic crossroad and that many parallels can be drawn between the photonic and the electronic evolution (see Figure 8). Both are building on the same strategic microfabrication technologies of sub-micron lithography and anisotropic etching. We have a tough road ahead but, if we slowly build university trained expertise in both electronics and microoptics fabrication and gain industrial acceptance, then the future will be bright. Microoptics is the quintessential enabling technology.

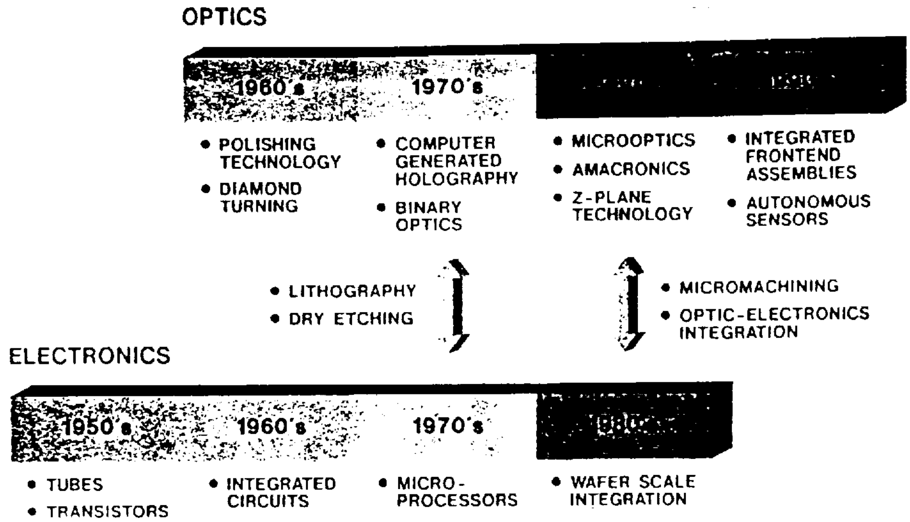

Figure 8. Parallel and Coupled Evolutions in Optics and Electronics

ACKNOWLEDGEMENTS

Over the years of the binary optics program, many people have contributed to the establishment of diffractive macrooptics and subsequently microoptics as a viable and reputable optics technology for systems. Foremost, I acknowledge the foresight of J. Lupo and L. Durvasula of DARPA and E. Wilkinson of the Army/SDC for their support in the various stages of the program. I thank my colleagues at MIT Lincoln Laboratory and numerous coworkers in industry. T. McHugh of Hughes Danbury Optical Systems and M. Riedl of Optical Filter Corp. particularly made significant contributions to the acceptance of the technology in systems. This work was funded by the Defense Advanced Research Project Agency. The views expressed are those of the author and do not reflect the official policy or position of the U.S. Government.

REFERENCES

1. E. Loewen, M. Neviere, and D. Maystre, "Efficiency Optimization of Rectangular Groove Gratings for Use in the Visible and IR Regions", Appl. Opt. , 18, p.2262, (1979).

2. G. Swanson, "Binary Optics Technology: The Theory and Design of Multi-level Diffractive Optical Elements", MIT Lincoln Laboratory Technical Report, 854 (1989).

3. M. Holz, M. Stern, S. Medeiros, and R. Knowlden, " Testing Binary Optics: Accurate High-precision Efficiency Measurements of Microlens Arrays in the Visible", These Proceedings, SPIE, San Diego (1991).

4. J. Leger, M. Scott, P. Bundman, and M. Griswold, "Astigmatic Wavefront Correction of a Gain-guided Laser Diode Array Using Anamorphic Diffractive Microlenses", SPIE Proc. 884, p. 82, (1988).

5. J. Leger, M. Holz, G. Swanson, and W. Veldkamp, "Coherent Laser Beam Addition An Application of Binary Optics Technology" , The Lincoln Vol 1, (2), p.225 (1988).

6. J. Horner, "ASAF Stresses Development of Semiconductor Lasers", Aviation Week and Space Technology, p.57, Jan 30, (1989).

7. M. Land, Handbook of Sensory Physiology, 8, p 471, (1982), Springer Verlag.

8. V. Wong and G. Swanson, "Binary Optics Interconnects: Design, Fabrication, and Limits on Implementation", These Proceedings, SPIE, San Diego, (1991).

MICROSENSORS, SMART SENSORS, SENSOR ARRAYS, AND THE ARTIFICIAL NOSE

by

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ABSTRACT

"Smart" sensors, or sensors connected to computers with intelligent software, offer new capability for chemical detection and monitoring. The human nose contains an array of differently selective receptors and an electronic preprocessing neuron network and is connected to a brain that can perform complex pattern recognition. Smart sensors and sensor arrays are now being developed that can begin to replicate the human olfactory process in function.

The field of microchemical sensors has experienced recent advances that allow the design of a variety of small sensor systems that are both sensitive and reliable. Examples include the thin film chemi-resistors, ISFETs, CHEMFETs, amperometric gas sensors, capacitance sensors, fiber optic [radiant] sensor systems, piezoelectric [mechanical] sensors, and microfabricated biosensors. Applications of microsensors include process control, indoor air quality monitoring, life support systems monitoring, effluent waste control, personal protection, and medical diagnostics.

Recent applications of "smart" sensor arrays include hazardous waste detection and identification and the determination of the quality of food [grain] prior to human consumption. At this time, sensor arrays have used relatively simple signal processing and pattern recognition. A comparison of a K-nearest neighbor [KNN] pattern recognition algorithm and a simple neural network [NN] intelligent system has revealed that the NN is better able to handle sensor array data and provide useful user output. The NN can deal with real applications and problems of sensor arrays such as multidimensional drift, sensor failure, and electronic noise. NNs that employ algorithms based on a "layered-model" of the natural olfactory system and are self-organizing [e.g., Kohonen networks] should be even more powerful [and more selective] than the simple algorithms now in use with sensor systems.

The opportunity exists to combine the microchemical sensors and the microelectronics systems to produce intelligent chemical recognition systems. The above examples are only the beginning.

Microtechnologies
and
Applications to Space Systems Workshop

APPLICATION OVERVIEWS

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Micromechanical Actuators

William Trimmer
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Belle Mead Research, Inc

Man has been developing tools and devices on the size scale of his hands for millennia. Cooperative efforts have also made substantially larger mechanical systems such as cranes, ships, and even canals and roads possible. It is interesting then, that substantially smaller systems have not seen the same development. Recent work, however, has demonstrated that micro structures and actuators can be made.

Micro mechanical devices have several advantages, especially when handling small parts. First, small systems tend to be fast, in part because the transit distances are smaller. Second, perturbations due to temperature expansions and vibrations, become smaller as the systems become smaller. Third, small systems have the obvious advantage of consuming less space. Fourth, the smaller forces required to move micro systems are more compatible with handling fragile things. And fifth, because the material costs of small systems scale as the third power (the volume), material costs are reduced, and exotic materials can be used that have desirable properties.

A number of forces scale advantageously into the micro domain. For example, hydraulics, pneumatics, and biological forces scale as the dimension to the second power. These forces become stronger relative to inertial forces that scale as the dimension to the third power (the volume). If the E field is constant, the electrostatic field also scales as the second power. Often the E field can be increased for small systems, and electrostatic forces have an even more advantageous scaling.

In situ Meteorological Sensors for Earth and Mars

by

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The requirements for in situ meteorological sensors which measure wind speed, wind direction, pressure, temperature and humidity, the primary variables of Earth and Mars, are presented. Ideal designs maximize accuracy, specificity, resolution, and reliability, while minimizing size, cost, complexity, weight and power. The importance of minimizing contamination of the measurement by the sensor, its support, and the surrounding spacecraft, will be illustrated using the Viking Meteorology Experiment. In some instances, such as Martian applications, the deployment is the driver rather than the lack of adequate sensor characteristics. Deployment, and measuring the very important vertical variation in the lower few meters of the atmosphere, can be greatly improved by microsensor development: other advantages of microsensors will also be described. The general status for each variable is discussed, as are the areas which need improvement. Instrumental enigma's, such as sensitivity to other environmental variables, or multiple types of interaction with the sensing elements, such as are found with water vapor, are outlined. Techniques for determining complex, multi-variable parameters from simpler measurements will be mentioned along with applications. Sensor aspects still requiring major development will be highlighted. Special attention will be directed to humidity measurement on Earth since it is by far the most important greenhouse gas, and it currently can not be satisfactorily measured in some of the most important applications critical to understanding the global climate and its potential for significant change. Without adequate humidity measurements, climate modeling will remain a resource consuming exercise with little chance of reasonable accuracy, until models can be compared with accurate space-time measurements of water vapor, clouds and snow and their effect on the radiative balance of Earth.

Silicon Flexural Microelectromechanical Devices

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Many applications of silicon microelectromechanical systems (MEMS) will require using the batch fabrication as well as the miniaturization of silicon VLSI technology. Silicon micro-electromechanical components can be used to implement complex mechanical functions through interconnections among a large number of mechanical components, each of which is relatively simple. Following a review of the design, fabrication and operation of early, discrete microactuators, we discuss the fabrication and operation of some flexural, suspended support, electrostatic microactuators designed as components for multi-actuator systems: a non-resonant, comb-drive actuator with sub-micron, interelectrode gaps achieved without submicron etching; a parallelogram actuator which transforms both the magnitude and direction of the attractive, electrostatic force; and a vertically-deflecting, electrostatic/ pneumatic actuator. These flexural microactuators are inherently free from friction/wear evident in continuous-motion microactuators and are capable of producing sufficient motion for envisioned applications in sensors, photonics and biomedicine.

MICROMACHINING THE FUTURE

by Dr. Marc Madou
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ABSTRACT

The impact of microfabrication on the manufacturing industry will be much more profound than just the advent of some new sensors and actuators. Microfabrication constitutes a new way of designing and manufacturing all types of small parts by incorporating technologies borrowed from the semiconductor industry. This method of manufacturing is not limited to parts made out of silicon but involves materials such as ceramics, metals and all types of semiconductors and organic materials. In the first part of this talk, I will try to increase the awareness of the audience about micromachining by giving examples of micromachined parts for a very wide variety of applications. The remainder of the discussion will center on the maturity of various sensor technologies in different application fields and barriers to commercialization. Emphasis is on micromachined parts for biomedical use.

Learning From Biology--Motor Systems at All Scales

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Human muscle is made up of cells (fibers) that are essentially microactuators. Within each bulk skeletal muscle in man are also thousands of redundant micro-length-sensors (muscle spindle organs). There are also micro-force-sensors (Golgi tendon organs) in the collagenous connecting tissues including tendons and aponeuroses. The muscle fibers themselves are organized in motor units capable of delivering different amounts of force depending on the number of fibers in a unit. As force is required, units fire according to the needed force with the smallest force-producing units firing at smallest required forces, and the largest ones firing at largest forces. This scheme keeps the $\Delta F/F$ (i.e., fractional change in force) roughly constant as new motor units come on-line. Much about the organization of microelements in a macroscopic system can be learned from looking at working biological motor systems. For example, it is interesting that the microactuator in biological muscle is roughly the same from a flea to a whale. The number of microactuators, of course, is very dependent on the scale of the organism. How many actuators is optimal for a given application? Should the actuators be paired with sensors and local processors and, it so, what is a useful ratio of sensors to actuators? How should the mechanical and control system be structured? All of these are questions for which guidance can be obtained by understanding biological motor systems.

In our research we are using SLIM (a six-link planar robot) as a platform to understand principles of the control of movement derived from biology. SLIM is structurally like man and so are his control systems. SLIM is a light-weight redundant system with five joints (ankle, knee, hip, shoulder, elbow) that are controlled by antagonist pairs of muscle-like actuators. The actuators, known as Rubbertuators (Bridgestone Corp.) are soft pneumatic bladders that, when inflated, contract 20% of their length. Like human muscle they are compliant. Length and force sensors are affixed to each artificial muscle.

We are using biologically-inspired algorithms to solve the inverse kinematics problem of the redundant structure and introducing reflex-like joint coordinations to improve posture management. The low-level posture controller is an iterative forward approximation scheme derived from a study of spinal frogs. The algorithm is parallel in nature and we are developing a specialized architecture of parallel digital signal processors (DSP--TI320C25) that mimics the organization of the human spinal cord to implement this algorithm. The parallel controller is being designed so that learning can be included at many different levels of the control hierarchy. The research is proceeding to use neural networks to learn how to integrate many levels of reflex control into smooth and efficient movements. Eventually, we would like to apply microtechnology to replace our crude artificial muscles with ones capable of more detailed control with the goal of efficiently performing the same dexterous and agile movements that man can carry out so well.

Micro-Software for Micro-Robots

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Abstract

Microtechnology has successfully reduced the size of processors, sensors, and actuators orders of magnitude from what they were a few years ago. This has allowed researchers to build a new breed of robots massing only a few kilograms (or in some instances grams) that have all of their functions onboard. This is quite an accomplishment compared to robots of only a decade ago whose cameras or computer would outweigh dozens of these current "micro-robots." Not to be outdone, software engineers and AI researchers have produced new robot programs that are more capable and orders of magnitude larger than the robot software that was available a few years ago. Despite the fact that today's micro-processors are more capable than yesterday's supercomputers, this new software will not fit on today's small robots.

It takes energy to store data in memory or to perform a computer operation. The more operations and data storage, the more energy is needed. Robots must operate in the world, in time to react to changes and events in their environment. The faster the robot needs to operate, the faster it needs to process its program, and the more power it needs for computation. The more power it needs for computation, the larger the power and thermal systems it needs to carry, which mean the larger (and more massive) its structure needs to be. The larger heavier its structure, the larger its actuators need to be, the larger its actuators, the more power they require. For space applications, the amount of software to be processed per second on a robot can have significant impact on the launch mass of the system.

Fortunately, AI research has also produced what has become known as "behavior control programming." Behavior control is an alternative method of programming robots (particularly mobile robots) which requires orders of magnitude less processing than traditional sense-plan-act control of these robots.

This task will review the current state-of-the-art in behavior control. Examples of its capabilities and limitations will be given. The role of behavior control in space robotics will also be explored.

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SPACECRAFT TELECOMMUNICATIONS TECHNOLOGY FOR MICROSPACECRAFT APPLICATIONS

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ABSTRACT

Spacecraft telecommunications systems traditionally consist of Radio Frequency Subsystems (RFS) and Antenna Subsystems. Fundamental trade-offs in system design are between power consumption, frequency and antenna size. Higher frequencies, such as Ka-band, result in systems with higher data rates, and low volume and mass, and enable use of electrically large antennas in a small physical envelope. These systems are at the state of the art for deep space telecommunications and are very costly to implement.

Development and space qualification of the following critical RFS technologies will yield significant savings to mass and volume, with lower cost than is available today. Application and integration with Microwave Monolithic Integrated Circuit (MMIC) devices with improvements in reliability through higher levels of integration, can reduce volume requirements by an order of magnitude; however, this technology is not space qualified at deep space frequencies. Research is also needed into rigorous modeling of MMIC packages and devices to reduce production iterations and to understand device interaction. Increased use of Application Specific Integrated Circuits (ASICs) to implement digital functions within the Transponder, Telemetry Control Unit and Command Detector Unit will likewise reduce mass and volume; however, research is needed to develop low power consumption MMIC and digital devices.

Antenna performance will dramatically benefit by development of space qualified MMICs for active array applications. Active arrays can replace bulky, massive TWTs and their associated high voltage power supplies by placing both the power amplifiers and low noise amplifiers at the aperture. Such arrays have the flexibility to be used as stand-alone small- to medium-sized apertures or to be used as feeds for reflector systems to efficiently realize larger aperture sizes. A key design challenge to implementing this technology is to provide a suitable thermal environment for the active components. Optically Processed Beamforming (OPB) is the ultimate step in

increasing overall telecommunications system flexibility and reducing system mass. OPB removes RF processing and components between the transponder and active aperture; transmission and distribution of signals to and from the aperture is accomplished photonically. Research is needed to develop photonic devices and tools to accurately model them in telecommunication system applications.

MICROSPACECRAFT: A CONCEPT

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ABSTRACT

There is need for smaller, faster, more frequent space science missions. Smaller spacecraft may enable such missions. Technology has been developed by the United States' Department of Defense and other government agencies that can enable smaller spacecraft. This author has developed a generic concept for utilizing advanced technology to create a microspacecraft. A microspacecraft would have a mass on the order of 10 kg. This paper will present this microspacecraft concept.