Optical MEMS-Based Arrays

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ABSTRACT

Industrial Micro Electro Mechanical Systems (MEMS) developers are rapidly bringing to demonstration inertial, radio frequency, and optical MEMS devices and components. The Army has a requirement for compact, highly reliable, and inexpensive laser beam steering components for missile seekers and unmanned aerial vehicles remote sensing components to provide a fast scanning capability for pointing, acquisition, tracking, and data communication. The coupling of this requirement with recent developments in the micro-optics area, has led scientists and engineers at the Army Aviation and Missile Command (AMCOM) to consider optical MEMS-based phased arrays, which have potential applications in the commercial industry as well as in the military, as a replacement for gimbals. Laser beam steering in commercial applications such as free space communication, scanning display, bar-code reading, and gimbaled seekers; require relatively large monolithic micro-mirrors to accomplish the required optical resolution. The Army will benefit from phased arrays composed of relatively small micro-mirrors that can be actuated through large deflection angles with substantially reduced response times. The AMCOM Aviation and Missile Research, Development, and Engineering Center (AMRDEC) has initiated a research project to develop MEMS-based phased arrays for use in a small volume, inexpensive Laser Detection and Ranging (LADAR) seeker that is particularly attractive because of its ability to provide large field-of-regard and autonomous target acquisition for reconnaissance mission applications. The primary objective of the collaborative project with the Defense Advanced Research Projects Agency (DARPA) is to develop rugged, MEMS-based phased arrays for incorporation into the 2-D scanner of a LADAR seeker. Design challenges and approach to achieving performance requirements will be discussed.

Keywords: Optical MEMS, Micro-mirrors, Phased arrays, Optical scanner

1. INTRODUCTION

The primary purpose of conventional phased arrays is to replace mechanical beam steering and stability mechanisms for more precise and rapid scanning capability. This subject is well documented in Ref. [1] for microwave and radio frequency systems. Phased arrays are replacing horn antennas to take advantage of rapid beam steering without mechanical manipulation. Recent progress in optical MEMS significantly impacts all aspects of RF and microwave radar, as discussed elsewhere Ref. [2]. Two related issues, optical phased arrays in the MEMS arena and the implementation of micro-optical components in LADAR seekers for missile systems and in communication links for unmanned aerial vehicles, are addressed in this paper.

Scientists and engineers at AMCOM AMRDEC have obtained approval to conduct a collaborative Army AMCOM/Army Research Laboratory (ARL)/Defense Advanced Research Projects Agency (DARPA) research and development program, "Phased Arrays for Tactical Seekers (PATS)," that will develop low-cost phased array components and designs, sub-arrays demonstrating RF and optical capabilities, and integrated phased arrays for missile communication links and seekers to provide an increased ability to track and engage multiple fleeting targets at increased range. Typical micro-optics components that are suitable for the 2-D scanner of LADAR seekers are discussed in this paper.

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This paper is arranged as follows. In the next section a brief description of a notional LADAR seeker is provided for general understanding of the military application. A quantitative discussion of some parameters specific to Army needs is also included. In Section 3, some recent work in optical systems designs and optical MEMS devices, which are relatively simple, but obviously provide building blocks for a more sophisticated system of LADAR seekers is presented. In Section 4, several alternative approaches to micro scanning systems are presented. In Section 5, a brief discussion of light sources ideal for Army applications is presented. A rudimentary design concept based on present optical MEMS technology is discussed and a brief summary is provided at the end.

2. NOTIONAL LADAR SEEKER DESCRIPTION AND REQUIREMENTS

Laser radars and/or LADAR seekers can be in a variety of forms depending on the applications. Some preliminaries based on radar in general and LADAR seekers in particular are presented,[3] prior to the presenting a description of a representative Army system.[4]

Using an optical wavelength around 1 μm or less has the advantage of small beam divergence, Θ, or lens diffraction limit, which is the ratio of the wavelength, λ, and the dimension of aperture, D. Roughly speaking the spatial resolution is on the order of centimeters in the kilometer range and the angular resolution is on the order of micro-radians. This high resolution is amenable to target recognition, as well as tracking. Thus, automatic target recognition software must be an integral part of the LADAR seeker operations. However, since the scattering cross-section is proportional to $1/\lambda^4$, optical seekers operating at small wavelengths suffer atmospheric attenuation, especially on foggy or rainy days. The best solution is to adopt a multimode seeker concept with constituent components operating at different wavelengths. This approach is being considered for future designs. A combination of microwaves for large area target searching and LADAR for target recognition would be ideal. One special feature of optical seekers used in the imaging system is that a minimal number of detectors can be used. Because of the minimal number of detectors and small angular resolution, scanning mechanisms are developed to image the object space. Fig. 1 shows how one detector can accommodate four points in object space. The extension of this set-up to multiple detectors develops a technique for focal plane arrays such that resolution cells in the object space are directly imaged into a mosaic of detectors, thus the entire scene can be registered simultaneously. These remarks lead to two most important questions for LADAR seeker design: how many detectors are required and what is the required scanning response time for a given set of requirements?

The Army is conducting and/or planning technology development projects that could benefit from affordable optical phased arrays for use in missile seeker and communication applications. Scientists and engineers at AMCOM are leveraging DARPA research and development projects in developing micro-optic components technology in support of reconnaissance-type missile systems and unmanned aerial vehicles. A set of typical design parameters, representing requirements for a notional LADAR seeker, is provided in Table 1. The air velocity of such a system is approximately 80 m/s while traveling at an altitude greater than or equal to 200 meters.

The LADAR scans a footprint of 80 m x 108 m in 0.75 seconds at a slant range of 648 m, as illustrated in Fig. 2. The airframe searches targets at a depression angle of 18 degrees. The spatial resolution is 40 cm at 648 m range. The number of pixels is calculated using the detector field of view (FOV) = 0. 4 m/648 m = 0.62 mrad, elevation angle 2.2 degs (vertical), and field-of-regard 9.5 degs (horizontal). The required number of pixels, N, for one frame is

$$N = \left[\frac{(9.5 \times 2.2)}{(57.3 \times 57.3)} \right] \Big/ \left(.62 \times .62 \times 10^{-6} \right) = 16{,}559 \quad (1)$$

As explained earlier, in focal plane arrays many pixels must share detectors. In order to obtain the number of detectors, M, the search time must be known. The search time depends on many factors such as the speed of the missile to cover the range of interest for a decision. Assuming the search time to be 0.75 seconds (the total active scan time to cover the entire FOV [9.5 degs x 2.2 degs]), then

$$M = \frac{16{,}559}{0.75\,\text{sec}} * \frac{1.296\,\text{km}}{3 * 10^5\,\text{km/sec}} \approx 1 \quad (2)$$

is the minimum number of detectors. The actual number should be larger to take into consideration the response time required to read more frames to form a picture.

Scanner response time is especially important for LADAR seekers operating with a high pulse repetition frequency, which is not a topic of discussion in RF radar. In our optical system, the most important requirement is the responsivity of the detector to each pulse. The effective pulse repetition frequency for the laser is 80 KHz. Each one of eight beams from the laser has an eighth of the laser pulse repetition frequency or 10 KHz, which requires a response time of 1/10 KHz or 100 μsec. This is equal to the required scanner response time listed in the Table 2. Optical MEMS becomes more indispensable, since liquid crystals can hardly accommodate a response time less than 0.1 msec.

The parameters for the light source used in the notional LADAR seeker design are provided in Table 1. Starting with the laser pulse energy, then the laser peak power (laser pulse energy/laser pulse width) is P_{pk} = 200 μJ / 8 nsec = 25 KW. The average laser power, P, is the pulse energy times the pulse repetition frequency, or P = 200 μJ x 80 KHz = 16 W. These numbers are to be divided by N_b, the number of beams. Although, we are aware of the advantage of averaging a large number of pulses, N_p (N_p = time on the target *pulse repetition rate) in signal processing to improve the signal-to-noise (S/N), no discussion will be given in this paper.

The radar equation is examined for discussion. The conventional form for S/N is[3]

$$S/N = \left[\frac{P}{(4\pi)^3}/(kTBL)\right] * \left\{G^2\lambda^2 * \frac{\text{(Radar Cross Section)}}{R^4}\right\} \tag{3}$$

where kT*B is the product of noise (k-Boltzman's constant and T-temperature) and noise bandwidth, B, in units of energy/sec. L is loss due to propagation through the atmosphere. $G = 4\pi A_{ant}/\lambda^2$ is the gain factor and R is the range of the radar. A_{ant} is the antenna area. The conventional expression is modified for a LADAR using direct measurement for which the band noise kT*B is replaced by $(A*B)^{1/2}/D_d$, where D_d is the detectivity in the units of cm-$Hz^{1/2}$/Watt and A is the detector area.

The tracking accuracy of the LADAR depends on the magnitude of S/N. For example the range error, or range resolution, is roughly given by $\Delta R = 3x10^8$*pulse width*Δ[ln(S/N)], which is approximately 0.24 m, assuming that the ratio of S/N error, Δ(S/N), and S/N is 0.1.

Similarly, the angular accuracy is dominated by the beam width and divergence (the ratio of the wavelength, λ, and the aperture, D). Since an angular resolution of 0.62 mrad must be achieved for target recognition, the determination of target angular position within 40 cm at 648 meters is not difficult. The above analysis is an estimate, but provides a general idea of the parameters involved. Obviously, a larger S/N and smaller beam width or larger gain always helps the accuracy of any measurement.

3. CHIP-SCALE IMPLEMENTATION OF FREE-SPACE OPTICAL SYSTEMS

Typical optical components for free-space optical system consist of lenses, mirrors, refractive or diffractive elements, opto-mechanical support such as lens mounting, and adjustable structure and actuators or 2-DZ micro-positioners. Some techniques for integrating free-space optical systems onto a chip are presented in this section. Optical MEMS,[5] is the primary focus.

Fig. 3 illustrates a micro XYZ stage picking up and moving an external micro ball lens. The base structure has five polysilicon plates. The center plate is the primary component of the optical elements. The two adjacent plates are used for support, whereas the other two plates are used for linear translation with integrated micro-actuators. The side support plates can rotate with respect to the actuator plate and the center plate, respectively. Consequently the center plate can be located above the substrate with a desired inclination. Similar control can be made in the orthogonal direction. In essence, the structure has a three dimensional manufactuability. In addition, the dimension of the plate is about 100 μm, with resolution of movement approximately 2 μm. A focal length on the order of 300 μm can be easily designed. The speed is controlled by the scratch drive actuators, which may be too slow.

The subject of micro-lenses and the required actuation is still in the evolutionary stage and the description above is not final. We should mention that the scanning micro-lens could be integrated with vertical cavity surface-emitting lasers. Fig. 4 is a rudimentary sketch of the general idea. The potential use for Army applications will be discussed later.

Some recent developments are discussed to show how optical MEMS is adaptable to Army applications. In Ref. [6], electrostatic force is used for actuation with the purpose of better packaging, power consumption, frequency performance, and cost. This research is an example of advancing the state-of-the-art. The mirror is relatively large, measuring several hundreds of microns on a side, which needs large angular deflection for desired optical resolution resulting in longer response time. This new phased array of a few tens of microns in size is illustrated in Fig. 5. Notice the mirrors tilt clockwise and move up and down maintaining a proper desired phase to perform as phased arrays. The speed of motion has two facets. One is determined by the resonance frequency, and the other by a translation motion controlled through a movable comb tooth drive.

4. CONVENTIONAL MICRO SCANNING SYSTEMS

Different groups are engaged to produce some of the same type devices with the intention of improving scanning speed, providing multi-outlets, and developing techniques for easier manufacturability. Some simple devices are discussed in this section. The fiber coupler for a laser module is discussed in Ref. [7]. The set-up is very simple as illustrated in Fig. 6. The general purpose is to guide the laser beam to the fiber by manipulating and adjusting the micro-mirror. A silicon optical bench assembled on a chip is by no means new. However, in the conventional package the alignment during manufacture is costly and the maintenance to assemble the bulky components leads to misalignment and degradation of performance. This problem seems to find a solution in this work. The major components are the laser module, fiber, and a micro-machined mirror, which can be translated and tilted independently. The prominent feature is that an external monitor/feedback control system not only can locate the optimal position, but also is left in place as the integral part of the package for later alignment.

Another example is micro-scanners such as those presented in Ref. [8] for barcode readers. It is obvious that these devices are not new. The existing systems use polygon mirrors, which require reflecting surfaces of high quality. The cost and sizes become undesirable features. The scanner apparatus is shown in Fig. 7. The main component, scanning micro-mirror, is further explained here. The silicon-surfaced micro-machined scanning micro-mirrors is a resonant micro-scanner featuring a large scan rate, a relatively large scan angle, and low mass. The size of the mirror is 200 x 250 square micrometers. It is inclined at 60 degrees to the substrate controlled by a hinged slider at its back. The actuation is provided by a conventional electrostatic comb-drive, which almost produces no current. A bar hinged to the mirror in one end and comb-drive in the other end is connected through the comb-drive and mirrors. The maximum excursion of the shuttle comb from its rest position is 20 μm (peak-to-peak is 40 μm), which results in 15 degrees maximum scan angle, $\alpha_{s(max)}$, for the mirror or 30 degrees for laser beam deflection.

The dimension of scanning range, S, and the lateral displacement, X, of the laser beam in Fig. 7 is related through

$$X / S = \alpha_{s(\max)} \sin(\omega t) \tag{4}$$

where ω is the mechanical resonance frequency.

Notice that this is a forced oscillatory mechanical system. The frequency of the applied alternating current signal must be adjusted to the mechanical frequency ω for an optimal value of $\alpha_{s(max)}$, which is based on empirically verified data. X must be less than $S^*\alpha_{s(max)}$ for application, then the reading can be accomplished in one period on the order of milliseconds according to Ref. [8].

Optical MEMS micro-lenses, mirrors, and gratings are essential building blocks for a simple scanning system as well as complicated ones. These examples, fiber-laser module coupler and barcode reader, are not the final word on the subject, especially when the cost and complexity of the system become critical factors. In the next two sections, some conceptual design approaches based on these building blocks are discussed.

5. DISCUSSION OF LIGHT SOURCES

An important component of a LADAR seeker is many adequate light beams. Vertical-cavity surface-emitting lasers (VCSEL) are essential for applications requiring high-density, two-dimensional array of lasers. One example of the most recent accomplishments is described to show the maturity of the subject. Several years ago the wavelengths of VCSEL were in the undesirable region for communication, but the recent advances seems to indicate that 850 and even 1160 nm VCSEL are ready for commercial applications as reported in Ref. [9], however no VCSEL operating at 1.06 μm is reported. VCSELs must operate at 1.06 μm for our purpose. Another issue of great concern for military applications is the power provided by VCSEL. A glimpse of the literature indicates that typical power is about several milli-watts on CW operation. The threshold values are a few mA coupled with several Volts. It seems a pulse of 30 μJ is a good estimate, when VCSEL is operated in the 10 millisec-pulse regime.

More stringent requirements are placed on VCSELs to meet the military requirements that are vastly different from communications in terms of pulse width, pulse repetition rate, and beam expansion. The unavailability of micro-laser sources to accommodate optical MEMS poses a serious problem. Consequently, the conventional laser source must be used in our program, with the anticipation that micro-lasers that meet the military requirements may be available in the near future.

6. OUR RUDIMENTARY DESIGN CONCEPT

The primary objective of AMCOM's optical phased array project is to develop MEMS-based phased array technology that could potentially replace the gimbals in current LADAR seekers. A schematic of a typical LADAR seeker composed of a telescope, which is controlled in azimuth by gimbals (not shown), is depicted in Fig. 8.[10] Our gimbaless MEMS-based 2-D scanner design concept is shown in Fig. 9, where the telescope has been replaced with a strapdown component. The primary function of the 2-D scanner is to ensure proper transmission of the laser beam to the target. The scanner consists of arrays of cascaded micro-lenses[11] that permit laser beam steering in both azimuth and elevation. The secondary function of the 2-D scanner is to collect the reflected light and ensure proper transmission (angle and phase control) to the detector for signal processing.

The LADAR seeker design for small missiles and air vehicles is somewhat simple. First, the relatively short range, 648 m, demands lower laser power for acceptable signal-to-noise ratio (S/N). A critical element of the 2-D scanner for a LADAR seeker is arrays of micro-mirrors for beam steering and phase control. An alternate approach is proposed in this paper. Ref. [5] is used as the major source for discussion. Refer to Fig. 4 where the Fresnel micro-lens is supported by a polysilicon plate, which is equivalent to the XYZ stage in Fig. 3. The output beam from a VCSEL under the Fresnel micro-lens can be collimated. Shifting the position of the lens can control the direction of the beams. In other words, the beam steering mechanism is executed by the plates in the XYZ stage. Furthermore, the steering speed is effectively controlled by the drive actuators, which must be operated in the KHz region in order to be compatible with the pulse repetition rate. In our design concept each array of micro-optic components functions as an addressable pixel, and the arrays of micro-optic components can operate independently or collectively. The laser beam is steered in both azimuth and elevation. The advantages of this design concept include increased scan speed and scanning angle.

The laser beam is required to have an angular resolution of 0.62 mrad, which is the minimum value of the beam width (the ratio of the wavelength and the scanner array diameter). Thus, the proper size of the scanner array is 1600 μm. If a 100 μm micro-lens is selected as a candidate for consideration, then an array of 16 (100 μm on a side) micro-lenses must be formed as one pixel, which has a size on the order of 4 mm x 4 mm, provided the assumption is made that an equal amount of space is used for actuation. In order to be effective, 1.7×10^4 pixels are needed as estimated earlier. Since VCSELs are not available for our purpose, the conventional light source in Table 1 is used, where a beam divergence at 0.15 mrad is required, therefore the reflected beam from a target 648 m away will cover an area approximately 10 cm in diameter. In other words, the number of arrays of micro-lenses should also be extended to cover the same area to capture the returned power. Considering the dimension of the array used above, then 40 x 40 arrays are needed. How to resolve this issue with optimal performance and cost will be an immediate concern.

The actuation of the micro-optic components must be addressed. Could the mechanical actuation described earlier, based on Ref. [5], be easily put together to form an array? Would other possibilities, Ref. [12], such as an electromagnetic optical scanner be more efficient? The answers are not currently known, but a few special features for LADAR seekers can be pointed out. Starting with the general set of requirements (cost, size, etc.) for successful optical MEMS components, the LADAR seeker in the notional design and the presently available optical MEMS are compatible but not desirable.

Other issues that must be addressed include automated optical alignment, dynamic tracking of optical interconnects, and actuation of multiple micro-optical elements encompassing the phased arrays. A set of models must be developed in order to understand the technical issues associated with phased sensor arrays for LADAR seekers. Concurrently with models development, micro optical devices currently under development at DARPA will be evaluated in the laboratory to verify the ruggedness of the devices over military environments. Emphasis will be placed on the performance of the micro-optical circuits under extreme temperatures, shock, and vibration. The results from the laboratory tests will be used to improve the models. The models and test data will be used to advance phased array designs and provide feedback to DARPA for design improvements in optical MEMS arrays.

7. SUMMARY

Our study of optical MEMS for LADAR seekers focuses on the 2-D scanner including beam steering, to which this paper is addressed. The increased speed of the micro-system over gimbals is one great advantage. Our review of a notional LADAR seeker proved not to be too strenuous both in terms of the data collection and imaging processing. As a result, the requirements for an affordable and compact system can be met by optical MEMS, at least in principle. A number of examples have been provided to show that micro-optics components for a 2-D scanner to be used in a LADAR seeker can, in principle, be reached without much difficulty. How to integrate various components as the building blocks for a workable system is not clear at this stage. Although we deal primarily with optical MEMS in this paper, it seems the role of liquid crystals should not be dismissed, unless the response time is pushed to less than 0.1 msec., which approaches the ultimate limit of liquid crystals.

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Table 1. Basic Performance Parameters for a Notional LADAR Seeker

PARAMETER	VALUE
Laser Pulse Energy	200 uJ
Laser Effective Pulse Rate Frequency	80 KHz
Pulse Width	8 nsec
Laser Wavelength	1.064 um
Beam Divergence at System Exit Aperture	0.15 mrad
Beam Diameter at System Exit Aperture	10 mm
System Angular Resolution	0.62 mrad
Range Resolution	0.15 m
Acquisition Scan FOV	AZ (9.5 deg) x EL (2.2 deg) 268 pixels AZ x 61 pixels EL
Active Scan Time	0.75 seconds
Missile Diameter	4.0 in
Maximum Diameter of Optics	2.8 in
Depression Angle	18 deg

Table 2. Basic Performance Parameters for a Typical 2-D Scanner

PARAMETER	VALUE
Scanner Response Time	100 μsec
Scan Efficiency (Elevation)	> 70 %
Scan Efficiency (Azimuth)	> 90 %
Scan Linearity	> 2%
Elevation Mirror Reflectivity	> 70 %

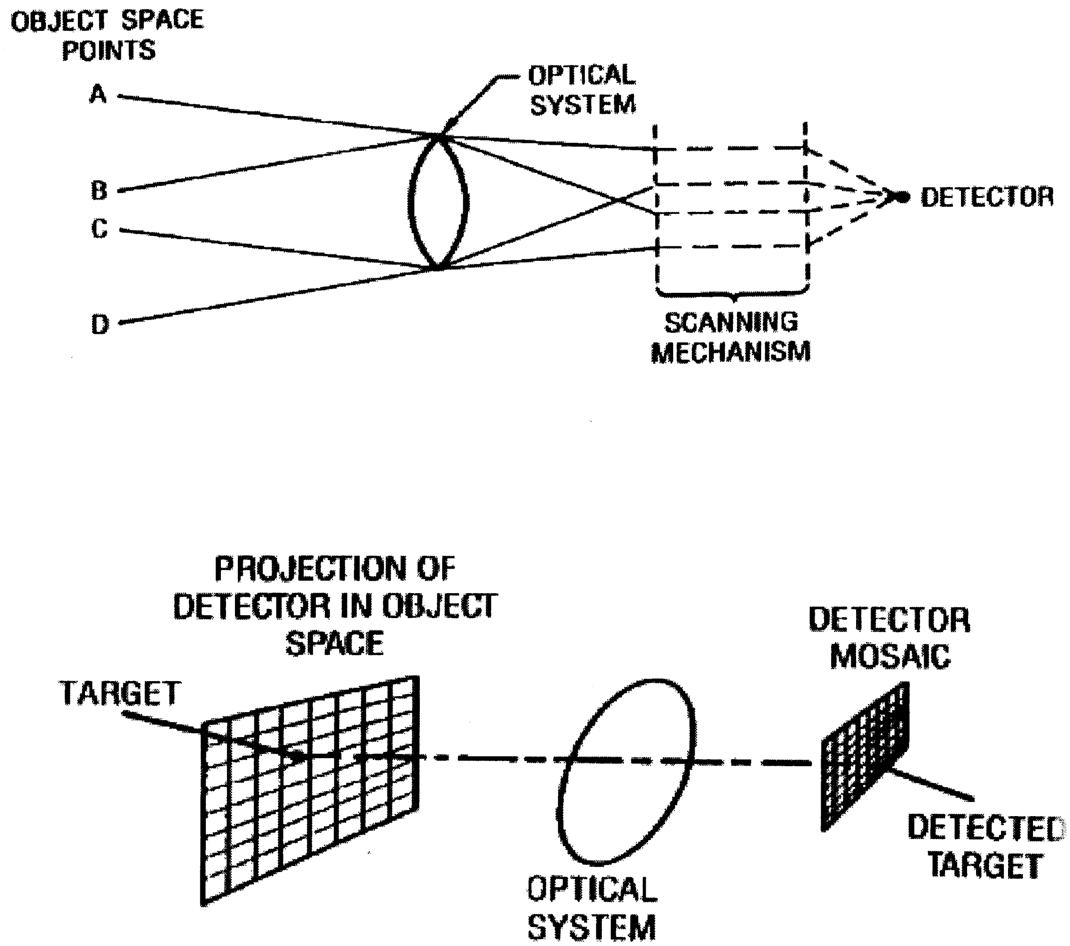

Fig. 1. Conceptual Diagram Illustrating the Basics of Focal Plane Array Imaging.

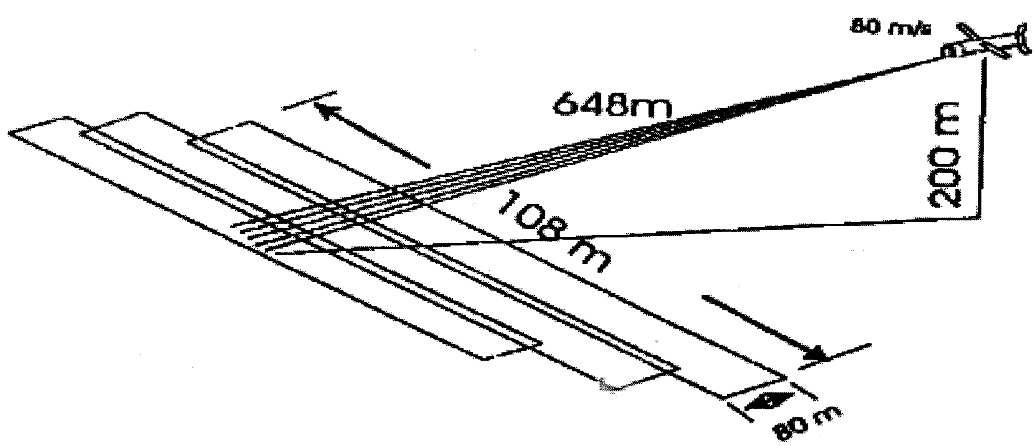

Fig. 2. LADAR Seeker Acquisition Scan Footprint.

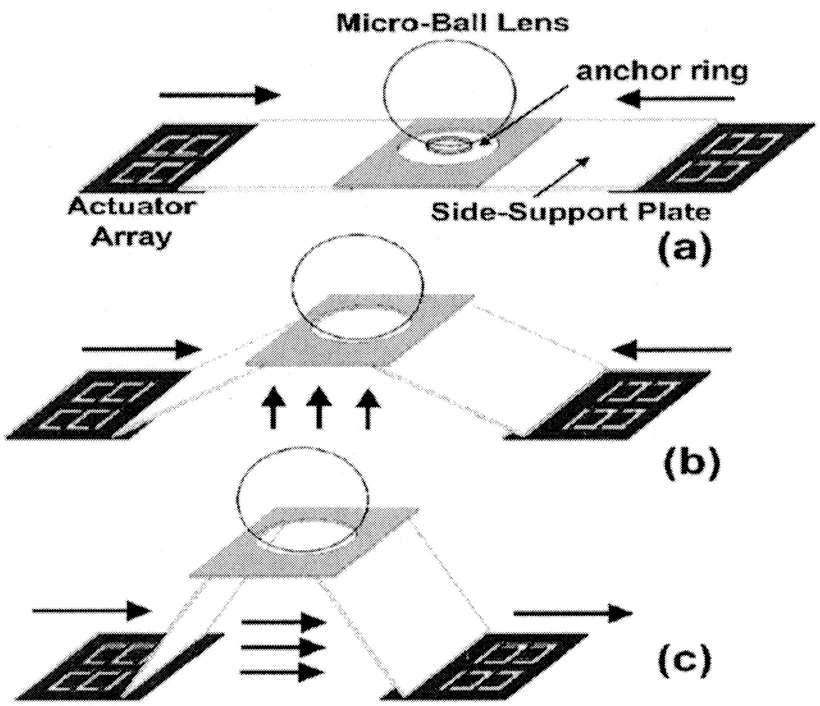

Fig. 3. Schematic of Micro-XYZ Stage Picking up and Moving an External Micro Ball Lens.

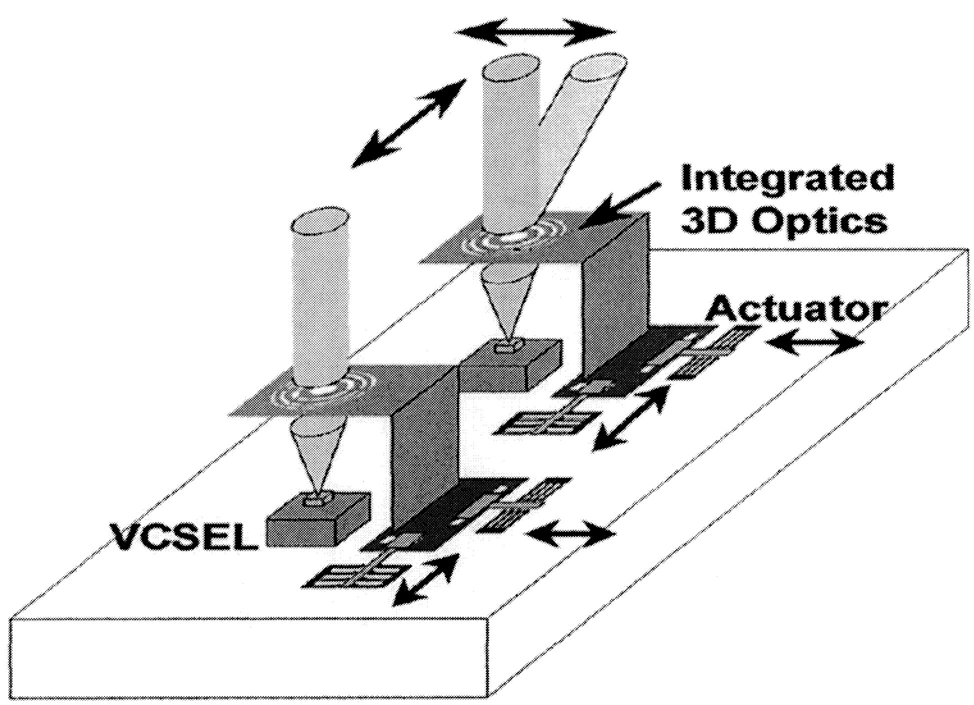

Fig. 4. Schematic of Scanning Microlens Integrated with Vertical Cavity Suface-Emitting Lasers.

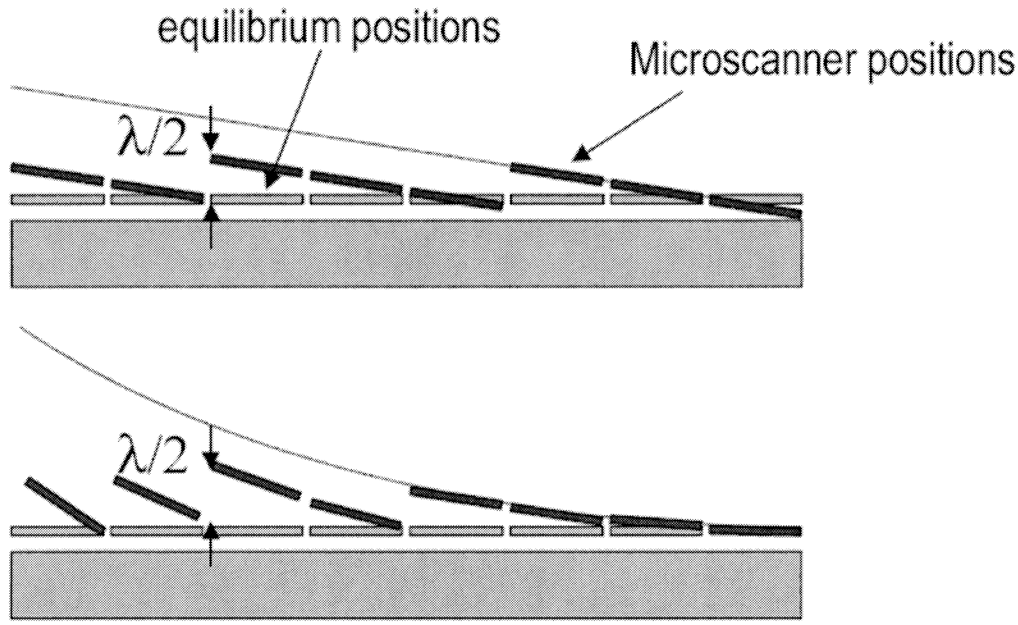

Fig. 5. Schematic Representation of the Operation of a Scanning Phased Array

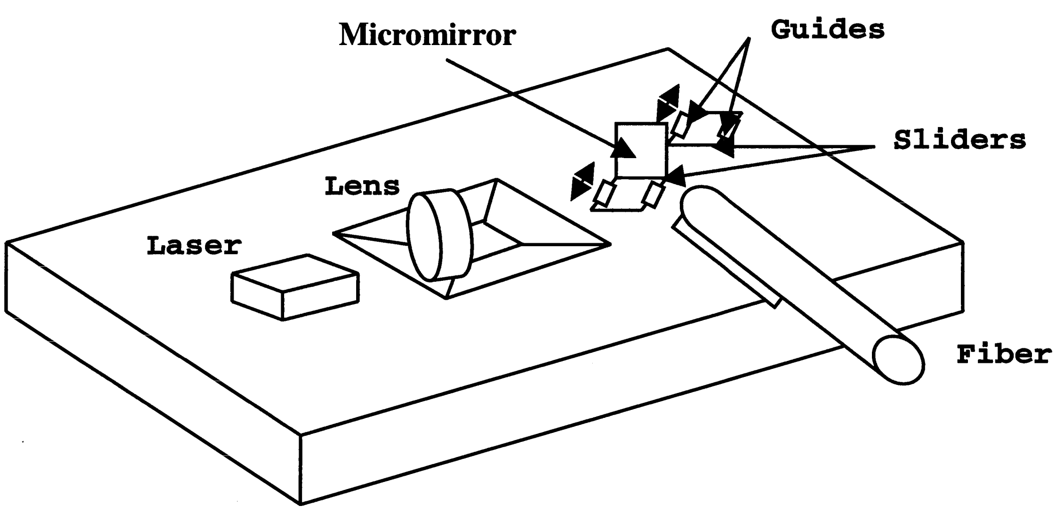

Fig. 6. Fiber-Coupled, Semiconductor Laser Module with On-Chip Alignment Mirror.

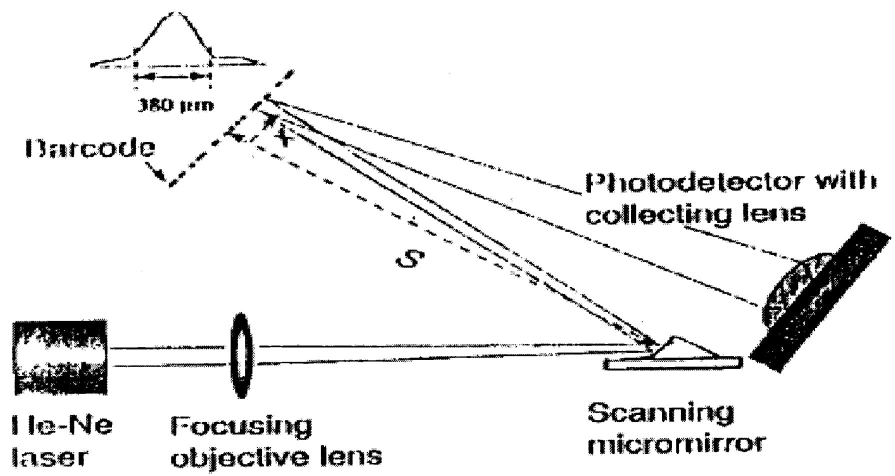

Fig. 7. Schematic of an Experimental Setup for Microscanner Characterization and Barcode Reading.

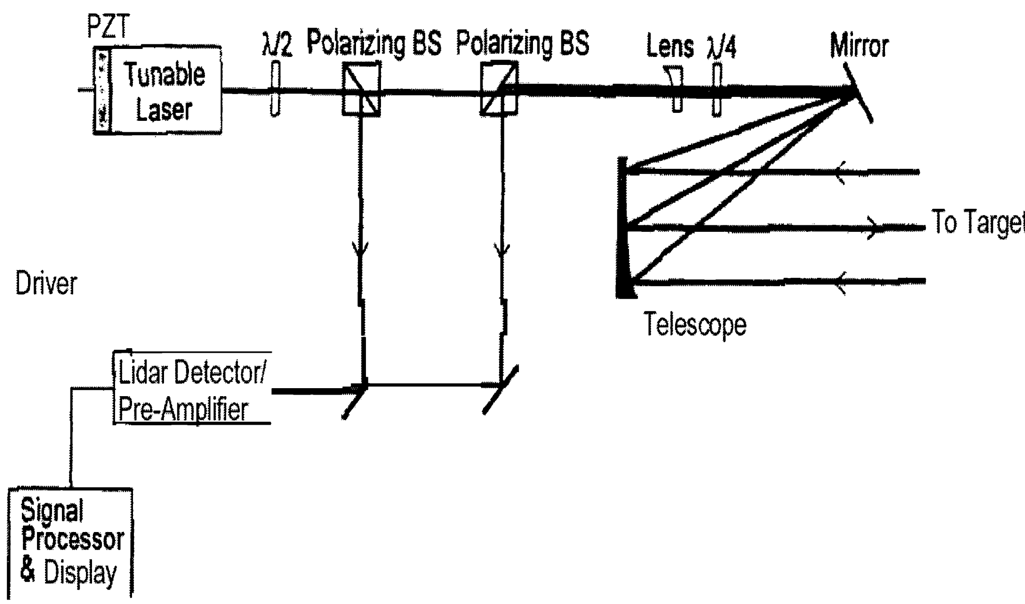

Fig. 8. Frequency-chirp Lidar Using A CW Tunable Laser

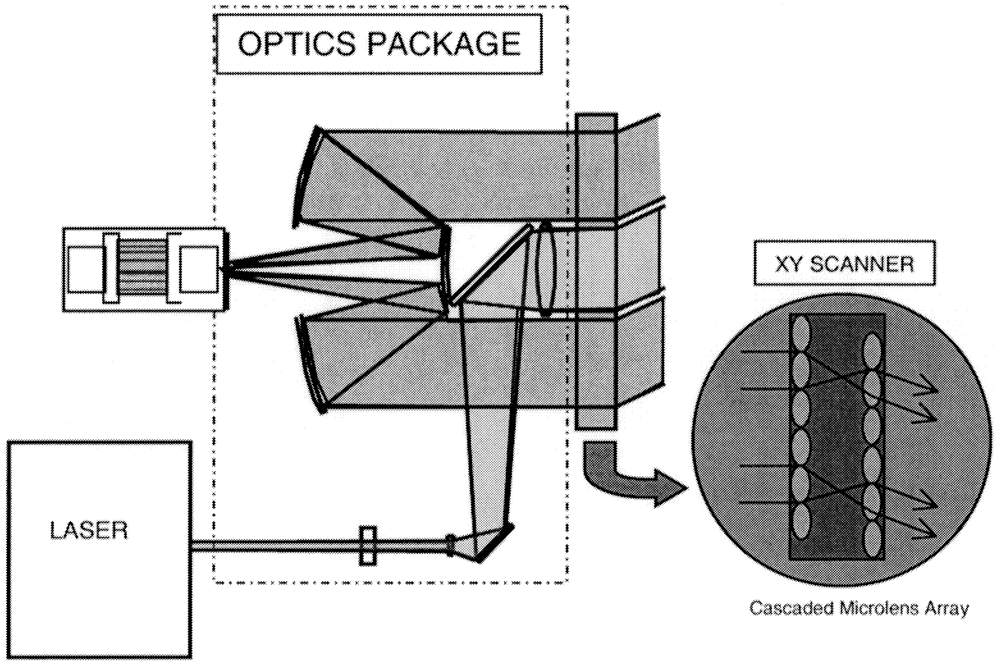

Fig. 9. MEMS-Based Phased Array Scanner