The potential of transmittive microoptical systems for miniaturized scanners, modulators and switches

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January 7, 1997

ABSTRACT

The utilization of microoptical components in systems for optical beam deflection and modulation offers the possibility for realization of miniaturized switches and scanners. As the required displacement of the microoptical components for efficient beam manipulation is quite small, high speed actuators with small electrical power consumption can be used. We present a variety of microoptical configurations and discuss their potential for the creation of different types of miniaturized scanners and switches. The combination of microoptical components already available and semiclassical piezoelectric actuators leads to new types of switching and modulation systems for a very broad spectrum of applications.

Keywords: microoptics, optical scanners, microoptical switches, piezoelectric actuators

1 INTRODUCTION

Most of the customary systems for optical beam-deflection and modulation are of rather big dimensions and require a considerable amount of electrical energy. Small dimension modulators of low switching power can be realized using integrated optical circuits. However, they are well suited only for applications in single-mode optical fiber systems. The state-of-the-art integrated optical switches suffer from high losses and do not match the cross-talk requirements of many applications. For the modulation or steering of incoherent beams no concept exists using integrated optics.

In contrast, there is a number of microoptical concepts existing for beam deflection and modulation.[1,2] Due to the small element dimensions of microoptical components very compact, fast and low energy consumption switches, scanners etc. can be realized. The high flexibility of microoptical components and systems can be used to build up well-matched solutions for a variety of switching and modulation purposes on the base of different light sources. However, a series of essential problems has still to be solved for a future commercialization: Serious problems arise from the integration of the single microoptical elements to an optical system due to the high positioning accuracy and, partly, small dimensions of the components. It is not completely clear which actuator concepts for driving microoptical components in scanning and switching systems are most suited. Up to now, mainly piezoelectrical actuators have been used, which are at least well suited from their translation range.

SPIE Vol. 3008 • 0277-786X/97/$10.00

Consequently, there is a need for well-matched opto-mechanical concepts to be developed. Finally, some special development must be also performed in the field of microoptics technologies, as the different applications of microoptical beam deflectors require certain optical parameters (optical losses, cross-talk, beam quality), which can be met only with appropriate parameters of the microoptical components.

In this paper, we will present a number of microoptical concepts for steering coherent and incoherent beams. In Chapter 2 we will discuss general aspects of microoptical beam steering. Beam scanning systems for coherent beams, especially Gaussian beams, are presented in Chapter 3. In Chapter 4 we will present a concept for deflecting incoherent beams emitted by multimode fibers and discuss some applications. Finally, we will draw conclusions and discuss future work in this area.

2 GENERAL ASPECTS OF MICROOPTICAL BEAM STEERING

2.1 Microoptical scheme

In Figure 1 a schematic diagram shows the microoptical components which are necessary for a microoptical beam-deflector or scanner. The first element in the chain is the optical source. Therefore it is not surprising

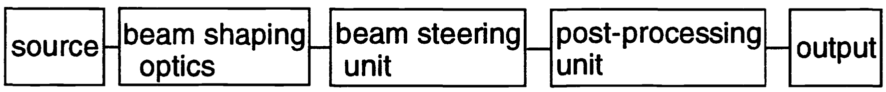

Figure 1: Principle of a microoptical beam-deflector or scanner

that the following optical elements have to be matched to the kind of source to be used. The concepts can be very different due to the wide range of optical sources. The beam shaping optics transforms the beam in a way that enables fast and energy-efficient steering. Some of the output parameters are mainly influenced by the beam shaping optics. This will become clear in Chapter 3 and 4. The central element is the beam steering unit. It comprises microoptical elements as well as a convenient mechanical actuator. Therefore, the system is actually an opto-mechanical system. The post-processing can e.g. be a collimation, fiber coupling or focussing onto a detector, working piece etc. . There are requirements to the:

- light losses
- resolution (number of resolvable beams behind the scanner)
- cross-talk between different steer positions
- beam quality of the steered beam
- switching time/modulation rate

The requirements which the system has to fulfill can be very different. To obtain attractive optical output parameters a careful selection of the optical components has to be done.

2.2 Actuation concept

The actuation concept is a critical point for microoptical scanners. As long as scanning is achieved by a mechanical movement of optical elements the switching times are restricted by the mass of the elements and the size of the displacements. Contrary to the concepts using mainly electrostatic, thermal or magnetic actuators in silicon in order to move micromirrors, thin grating structures etc., the microoptical components we use are of several tens of milligramms up to several gramms of weight, so those actuators are too week to be applied.[3–5] Many applications require switching times in the order of a few milliseconds which can be realized by means of piezoelectrical actuators. Customary piezoelectrical stack actuators are stronger by far as required in our application. Thus, in order to create piezoelectric actuators matched to the movement of microoptical components (weight, displacement range, speed) an other concept has been investigated. Bimorph piezoelectric layers are attractive candidates to achieve movements of several $10 - 100\,\mu$m. They consist of two connected piezoelectrical layers and act like a bimetal, operating in a bending mode. To achieve a translation in one direction, instead of a bending, two of the bimorph layers are combined to form a parallelogram. Figure 2 shows a planar and a cylindrical arrangement of such parallelograms, which are capable of two-dimensional motion. There is enough place for

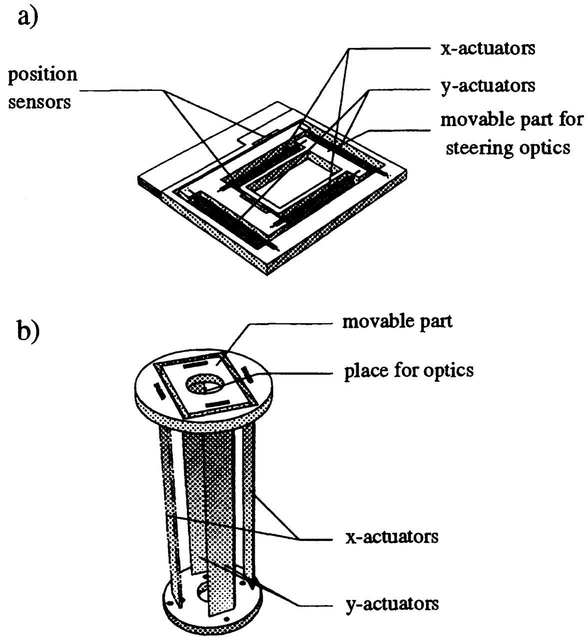

Figure 2: Piezoelectric bending actuators for optical beam steering: a) planar arrangement, b) cylindrical arrangement

microoptical elements in it. Sensors can be introduced for position detection. The maximum displacement can be adjusted using the right length of the layers. Prototypes with various length, stiffness have been realized with maximum displacements between $20 - 200\,\mu$m. Typical resonance frequencies are 0.1–0.6 kHz with switching times of a few milliseconds.

3 DEFLECTION OF GAUSSIAN BEAMS

Considering a Gaussian beam with a waist radius of ω_0, the far-field divergence θ is given by $\theta = \lambda/\pi\omega_0$. The étendue, which is an appropriate measure for the space-bandwidth-product, is given by:

$$E_{Gaussian} = \pi^2\omega_0^2\theta_0^2 = \lambda^2 = const. \tag{1}$$

E is a constant and is conserved during the propagation through diffraction limited optical systems. Due to the small étendue Gaussian beams can combine a small waist diameter of the beam with a moderate far-field divergence (e.g. a Gaussian beam with $\lambda = 780$ nm, $2\omega_0 = 5\,\mu$m gives $\theta = 0.1$).

Therefore, a simple beam-deflection concept can be realized by focussing the incoming beam with moderate numerical aperture and placing very simple microoptical elements like lenses, prisms, mirrors into the focal plane of the focussing optics. The required mechanical displacements are in the order of 10 to some 100 microns and therefore very small.

The angular resolution is an important measure for scanning systems. The one-dimensional resolution for a beam-deflector, i.e. the number of spots N, which can be resolved, can be defined as relation between the maximum deflection angle and a characteristic angle, which describes the divergence of the outgoing beam (see figure 3).

$$N = \frac{\delta_{max}}{\theta} \tag{2}$$

Microoptics offers high-resolution as well as low-resolution devices by properly adjusting the deflection angle and

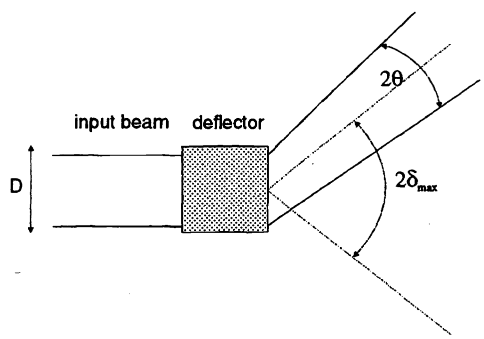

Figure 3: Definition of beam-deflector resolution

the divergence of the beam behind the deflector.

3.1 Concepts for low-resolution devices

3.1.1 Fiber switches

At present, there is a need for low cost, low loss, high channel-isolation fiber-optic switches with a wide range of applications in communication systems. Figure 4 shows a microoptical concept of a singlemode fiber switch driven by a piezoelectrical actuator. Switches for communication systems must have excellent optical parameters (low insertion losses, low cross-talk). The focussing onto the deflecting structure has to be diffraction-limited especially to ensure low cross-talk values. The deflected beam is coupled into an output fiber with high efficiency by means of

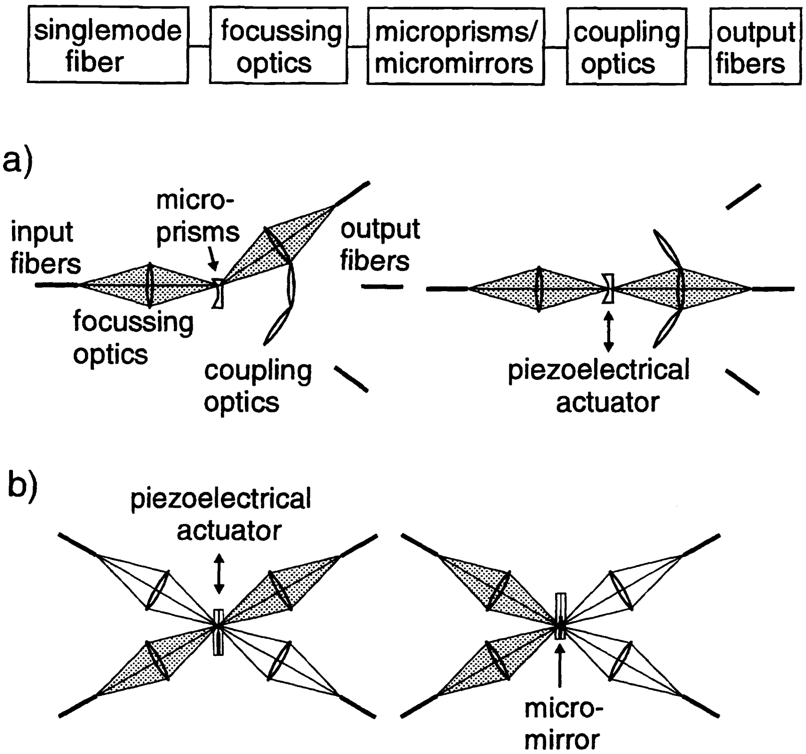

Figure 4: Principle of a microoptical singlemode fiber switch: a) 1x3-switch using microprisms, b) 2x2-switch using micromirrors

an appropriate designed coupling optics. In theoretical investigations we could show that it is possible to achieve high coupling efficiencies (above 95%) using aspheric focussing and coupling optics with the microprisms being on a thin substrate, thus reducing the wavefront aberrations. In experiments, we used moulded aspheric lenses for focussing and coupling and fabricated microprisms by anisotropic wet chemical etching in silicon, obtaining a master for subsequent replication into polymers. A beam emitted by a singlemode fiber ($\lambda = 780$ nm) was focused to a spot of $2\omega_0 = 5\,\mu$m. In order to avoid diffraction effects at the deflecting element the prism width was chosen to be $4\omega_0 = 10\,\mu$m. The prism angle was 35°. This results in a deflection angle of 18°. For that singlemode fiber switch, we obtained low insertion losses (< 1 dB) and low cross-talk between the output channels (< -50 dB). The wide angular spectrum of the Gaussian beam is the reason for the remaining cross-talk. The switching time was around 1 msec. The lateral alignment tolerances of the microprisms are low ($\pm 0.5\,\mu$m), thus giving relaxed requirements on the repeatibility and the stabilitiy of the actuator, which is a major advantage in using microprisms instead of continous surface profiles for beam-deflection. A detailed description of the theoretical investigations and the experiments has been given recently.[6] The crossbar fiber switch with metal micromirrors embeded between two substrate layers gave similar results for the coupling efficiency, cross-talk and switching times.

With the help of equations (2) the resolution N is determined by the maximum deflection angle δ_{max}, i.e. the prism angles in Figure 4 a), and the waist radius ω_0 of the laser beam in the focal plane.

$$N = \frac{\pi \omega_0}{\lambda} \delta_{max} \tag{3}$$

For example with $\lambda = 1.55\,\mu$m, $\omega_0 = 5\,\mu$m, $\delta_{max} \simeq 30°$ one obtains a one-dimensional resolution of $N = 5$ which corresponds to the number of output channels. A displacement of $4\omega_0 N = 100\,\mu$m is required to adress the single switching states. The number of output channels can be increased, using a two-dimensional arrangement of microprisms. It can be further increased choosing a larger ω_0 which results in a decrease of the divergence of the beam behind the deflector. For example with $\lambda = 1.55\,\mu$m, $\omega_0 = 10\,\mu$m, $\delta_{max} \simeq 30°$ one obtains a resolution of $N = 10$. However, this will increase the required maximal displacement to $4\omega_0 N = 400\,\mu$m which results in an increased switching time.

3.1.2 Aspects of system integration

Contrary to on chip solutions there is no possibility of merging directly together the microoptical element and the microactuator in our case. All the microoptical elements are initially existing in a separate form and must be assembled together and to the actuator to be used with defined tolerances in relative position and orientation. Usually these alignment tolerances are very small. Up to now, no standard handling and mounting techniques exist for microoptical components. For stability and reliability reasons the systems discussed above should be realized as compact as possible and passive alignment approaches should be preferred. Figure·5 shows two examples of miniaturized fiber-optic switches where these considerations have been already observed.

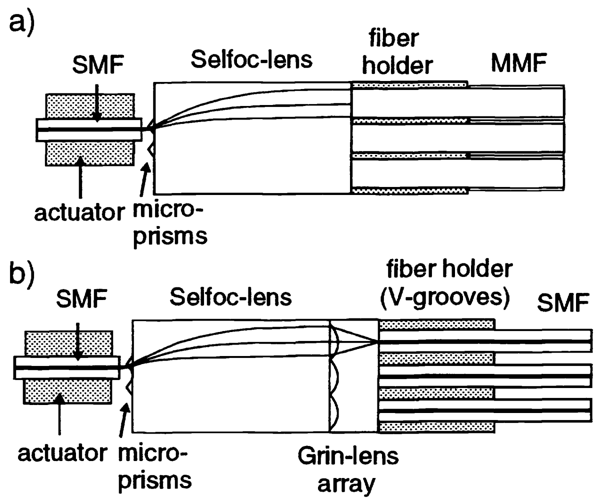

Figure 5: System integration of a fiber switch: a) singlemode fiber to multimode fiber switch b) singlemode fiber switch

Polymer microprisms were replicated onto the input surface of a Selfoc-lens with quarter pitch length, which collimates the deflected beams. The input fiber is brought close to the prisms. If the prisms are situated within the Rayleigh-range of the beam emitted by the fiber the beam-spread can be ignored. Multimode fibers can be placed at the end of the Selfoc-lens for direct coupling. For coupling to singlemode fibers or multimode fibers with small core an array of Grin-lenses (graded index lenses) can focus the beams to the fibers. All elements are cemented together and give a very small device with a volume of a few mm^3. We built up configuration a) with multimode fibers with a core diameter of $200\,\mu$m, a Selfoc-lens (H-1.8-0.25-0.63) and a metal fiber-holder with $200\,\mu$m-holes made by precision drilling with a CNC-machine. Because of the collimating function of the Selfoc-lens no fiber cladding is required within the fiber-holder. We obtained efficiencies of 50% with a cross-talk of -20 dB. These values can be increased by far using optimized optical components. For this system the étendue of the input and output fibers do not match which results in beam degradation for the sake of higher functionality namely possible switching to different fibers. Configuration b) is a more sophisticated device with input and output fibers having the same étendue. To achieve sufficient optical parameters an optimization of the Selfoc-lens and the Grin-array has to be realized.

3.2 Scanner with medium resolution

From equation (2) it is obvious, that the resolution can be increased, when the Gaussian beam leaves the deflecting device in a collimated manner, i. e. with small divergence. This can be simply obtained using a collimating lens which is decentered with respect to the optical axis (Figure 6). In order to fulfill the requirements

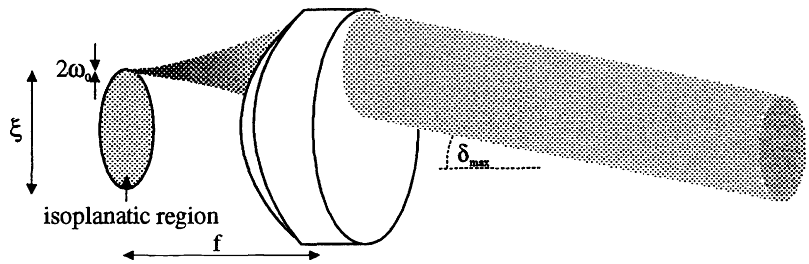

Figure 6: Beam-deflection with decentered, collimating microlenses

for the maximal deflection angle δ_{max} and the resolution N a suited setup with the following parameters has to be designed:

- lens system with appropriate focal lenght f, f-number $f\#$ and a large isoplanatic region with diameter ξ
- an incoming beam with waist diameter $2\omega_0$
- an actuator with maximal displacement matched to the extent of the isoplanatic region.

The maximal deflection angle δ_{max}, the resolution N and the lens diamter d, assuming that no vignetting occurs (at least 99% of the Gausian Beam illuminate the lens aperture), are given by the following equations:

$$tan(\delta_{max}) = \frac{\xi}{2f} \tag{4}$$

$$N = \frac{\xi}{2\omega_0} \tag{5}$$

$$d \geq \xi + 3\frac{\lambda}{\pi\omega_0}f. \tag{6}$$

However, in most of the applications the task is to create a scanner of certain deflection angle, resolution and switching time t. One has to design a proper lens system together with an actuator that fits these requirements. From the optic-design point of view it makes sense to translate the desired switching times to values of the maximal displacements, which have to be guaranteed by the actuator. From a set of certain δ_{max}, N, ξ one can derive the required values of $f, \omega_0, f\#$:

$$f = \frac{\xi}{2\,tan\delta_{max}} \tag{7}$$

$$\omega_0 = \frac{\xi}{2N} \tag{8}$$

$$f\# \leq \frac{1}{2\,\tan\delta_{max} + \frac{6\lambda N}{\pi\xi}}. \tag{9}$$

In Table 1 some examples for various situations are given. It is obvious that microlenses with low f-numbers are

Example	1	2	3
deflection angle δ_{max}	$\pm 10°$	$\pm 20°$	$\pm 50°$
resolution N	100	50	20
max. displacement ξ	$300\,\mu$m	$200\,\mu$m	$100\,\mu$m
focal lenght f	$850\,\mu$m	$275\,\mu$m	$42\,\mu$m
waist diameter $2\omega_0$	$3\,\mu$m	$4\,\mu$m	$5\,\mu$m
f-number $f\#$	1.28	0.95	0.38
lens diameter d	$664\,\mu$m	$289\,\mu$m	$110\,\mu$m
illuminated area $\frac{d-\xi}{d}$	0.55	0.31	0.09

Table 1: Design examples for various values of the deflection angles, resolution and maximal displacement ($\lambda = 0.67\,\mu$m)

required. However, since the illuminated area of the lens or the entrance pupil of the system is in some cases very small in comparison with the lens diameter, the lens does not have to be diffraction-limited for the whole numerical aperture. Instead diffraction-limited behaviour is required for telecentric illumination within a certain isoplanatic region with beams of moderate numerical apertures. Especially from example 3 it can be seen that only a small part of the lens is illuminated for each position.

Especially because of the high isoplanatism, graded-index lenses are attractive candidates to meet these requirements. The index-profile can be controlled to obtain nearly aberration free lenses. Converging and diverging lenses can be fabricated. Certain glasses allow high refractive index changes during the ion-exchange process delivering lenses with large numerical apertures.

Figure 7 shows diverging lenses in different lateral positions to an incoming, converging beam, yielding a collimated output. Such diverging lenses have been fabricated in slabs to obtain cylindrical lenses. In beam-deflection

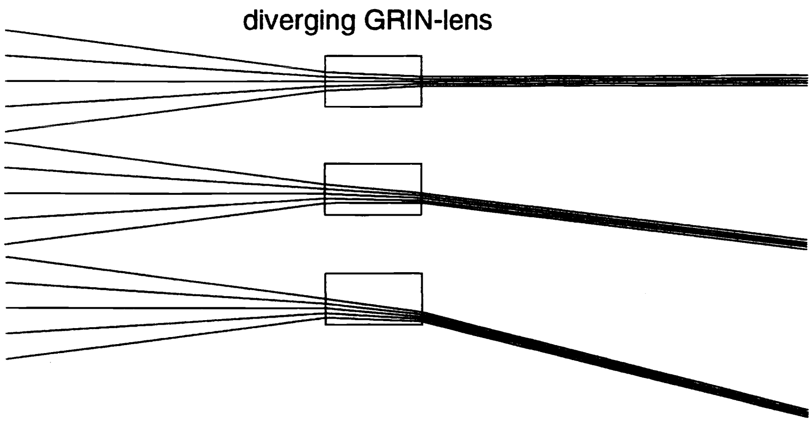

Figure 7: Beam-deflection with diverging GRIN lenses

experiments the relation between deflection-angle and displacement was measured.[7] For a typical cylindrical lens with a certain index-profile and a thickness of $500\,\mu$m a deflection/displacement of $0.43°/\mu$m was measured for an incoming beam with $\lambda = 0.67\,\mu$m and $\omega_0 = 2\,\mu$m.[8] δ_{max} was $30°$, the maximal displacement was $140\,\mu$m and the far-field divergence $\theta = 0.9°$. This corresponds to $2\omega_1 = 27\,\mu$m and a resolution of $N = 35$.

3.3 High resolution scanners

To achieve a high resolution scan, the aperture of the optics has to be increased further. This can be done using microlens arrays with the advantage that the displacements stay in the order of a single lens dimension d and therefore an agile beam steering is possible.[2] Figure 8 shows a typical setup with decentered lens arrays. However,

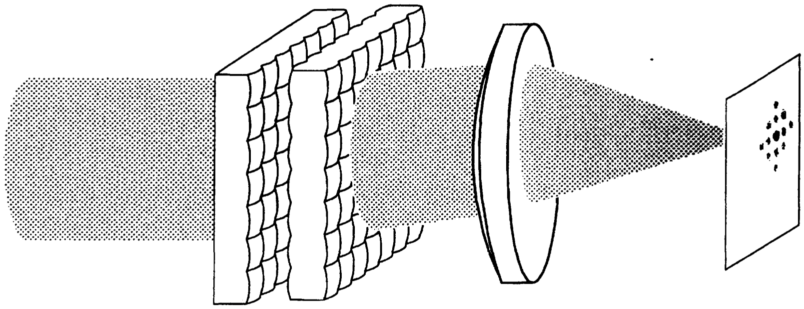

Figure 8: Beam-deflection with decentered microlens arrays

there are some shortcomings. The whole setup acts as a diffraction grating allowing efficient beam steering to discrete angles only.[9,11] To achieve deflection angles of 10° and more, aspheric surfaces of the microlenses are required. For high optical transmission the microlenses have to fill the area with fill-factors of 95% and higher. Coherent arrays are required. These problems have to be addressed by fabrication technologies for microlens arrays. In theoretical investigations it has been shown that deflection angles of 25° with diffraction limited performance and with a resolution comparable to galvanometer scanners can be obtained.[11] The resolution is given by the maximum deflection angle and the difference between discrete steer angles in the angle domain:

$$N = 2\delta_{max}\frac{d}{\lambda}. \tag{10}$$

The problem of the diffraction-grating behaviour can be overcome for certain pointing applications, destroying the periodicity of the lenslet arrangement (Figure 9). This will result in slightly increased light losses of the steered

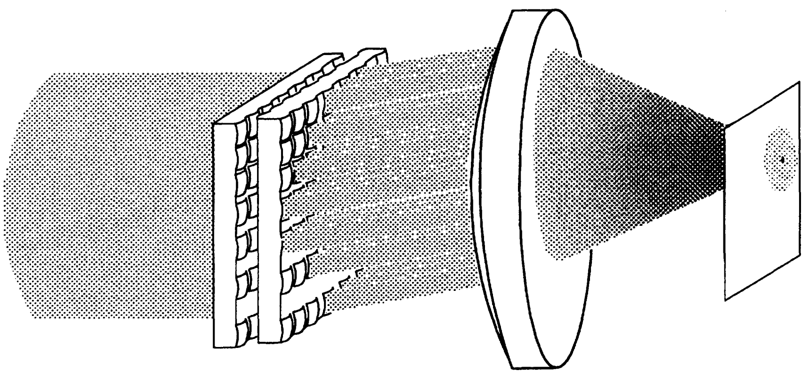

Figure 9: Beam-deflection with decentered microlens arrays and non-periodic arrangement of the lenslets within the array

beam and in a background intensity, which does not diminish the performance of the scanning systems in dynamic applications that detect differences in optical signals (e.g. reflectivity of an object).

4 SCANNING OF INCOHERENT BEAMS

As mentioned above the beam-deflection concept depends strongly on the kind of the input beams. Incoherent beams cannot be focussed with a single lens to spots of a few microns without high light losses. For instance the étendue of a multimode fiber with core radius a and numerical aperture $N.A.$ is given by:

$$E_{MMF} = 2\pi^2 a^2 N.A.^2 \gg \lambda^2 = E_{Gaussian}. \tag{11}$$

The étendue is much higher than the étendue of a Gaussian beam. Therefore displacements in the range of some 100 microns to millimeters are necessary to deflect the beam with conventional optics. This will reduce the switching time to unexceptable values. For efficient manipulation of incoherent beams lens arrays are required resulting in a segmentation of the input beams. Generally, the same setup like in figure 8 can be used. A small spot behind each lenslet of an array is generated. The étendue of the single beams is reduced and the single beams are spatially separated (Figure 10). The reduction in the étendue of the single beams is given by:

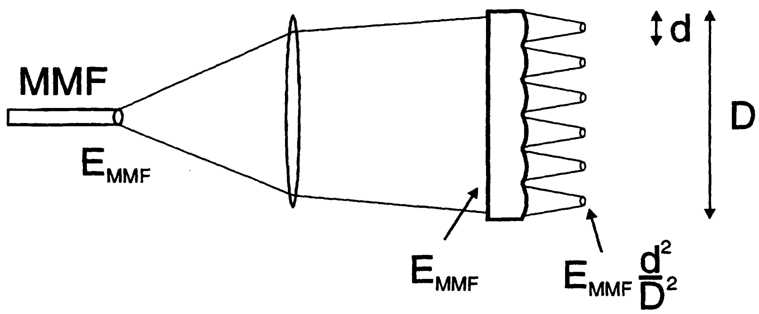

Figure 10: Separation and étendue reduction of incoherent input beams with microlens arrays: E_{MMF}...étendue of the multimode fiber MMF, $E_{MMF}d^2/D^2$...étendue of the single beams behind the lens array

$$\frac{E_{sep.beam}}{E_{MMF}} = \frac{d^2}{D^2}. \tag{12}$$

The spot size and the divergence of the beams can be adjusted choosing appropriate focal lengths of the microlens arrays and the collimating lens. The single beams can now be manipulated efficiently combined with small displacements. The coherence between the single beams is not destroyed if the focussing lens array and the manipulating element consist of coherent elements. Therefore the problem of the grating behaviour of the lens arrays does not vanish. However, a proper choice of the beam divergence in front of the first microlens array solves this problem. If the beams leave a single lenslet of the second array with a divergence much larger than λ/d, which gives the angular separation of the diffraction orders, then the grating behaviour can be neglected because the single diffraction orders overlap in the angle domain. Therefore such a device can be used for steering light emitted by multimode fibers or even fiber bundles and can be quite efficient.

In order to demonstrate the function we used cylindrical lens arrays in a confocal arrangement for steering a beam emitted by a multimode fiber with a core of 200 μm. The setup is shown in Figure 11. The lenses are made of quartz with a lens pitch of 400 μm and f-number of 5. The surface profile was spherical within 80% of the single

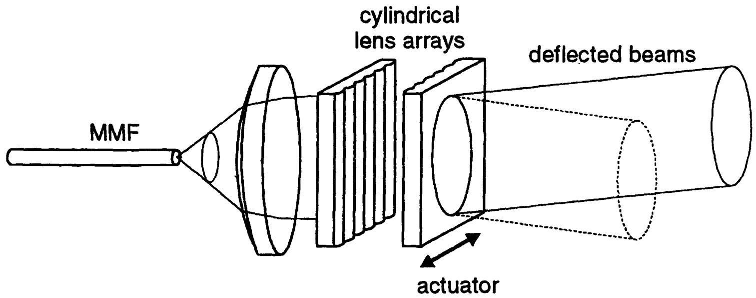

Figure 11: Beam steering experiment with lens arrays in a confocal arrangement and incoherent illumination

lens. The lens arrays are commercially available from the german company LIMO. In front of the focussing array we realized a beam with $\lambda = 670$ nm and a divergence of $2\theta = 17 mrad$. The focussed light was concentrated in a number of lines of $40\,\mu$m lateral dimension in the common focal plane of the arrays. The recollimated beam contained 60% of the energy for the unsteered case. We could steer in one dimension to maximal $\pm 5°$ with displacements of $\pm 160\,\mu$m. The efficiency decreases with increasing steer angle due to vignetting. For the edge of the scan field two beams with deflection angles of opposite sign appear and the efficiency was only 30%. The results can be improved using lens arrays with a higher optical fill-factor and avoiding vignetting with a field lens array.[9] The lens array material can be used for high-power laser applications.

Generally, problems arise from the incomplete fill-factor of the arrays (cylindrical arrays are more suited than two-dimensional lenses), the aberration performance of the lenses (aspheric surfaces are required for faster lenses) and inhomogenities of the lenses of an array (variation of the focal length). These have to be adressed by fabrication technologies.

There are a plenty of applications for fiber switches, adaptive illumination systems, scanner for material processing. Applications for imaging devices with variable or switchable steer angles exist in inspection and security systems.

5 CONCLUSIONS

We showed that a lot of microoptical concepts exist for low- and high resolution beam-deflectors even for a broad spectrum of light sources: laser beams, various types of optical fiber output beams etc.. In Figure 12 the various concepts for microoptical laser-beam deflection are summarized. For applications with Gaussian beams and moderate output beam requirements standard microoptical components such as Selfoc-lenses, ball-lenses, aspheres etc. can be used as single elements, assembled to a defined system. Special non-standard microlenses, however, must be used for optimum resolution behavior. Special microprisms are attractive candidates for the realization of fiber-optic switches with discontinuous beam-deflection, where systems with negligible abberations have been realized. Arrays of microlenses, microprisms etc. can be used for deflection of incoherent beams (multimode laser beams, multimode fiber (bundle) beams). However, in order to achieve optimum optical performance, the important array parameters must be improved (high fill-factor, homogeneity of lens shape, aspherical shapes).

Besides piezoelectrical actuators other actuator concepts with lower voltage and no hysteresis should be tested for moving microoptics. Finally, a considerable effort is required to overcome the apparent problem of assembling the rather complex microoptical systems.

deflecting elements	microprisms/ micromirrors in convergent beams	decentered, collimating microlenses	decentered microlens arrays
typ. resolution (one-dimens.)	5	20-300	500-1000
applications	fiber switches	illumination systems, optical inspection, bar-code reading	optical inspection, material processing, optical metrology

Figure 12: Summary of the concepts for microoptical laser-beam deflection

6 ACKNOWLEDGMENTS

The present work was supported by the Federal Ministry of Education and Research (BMBF), FRG, within the national joint project "PIMOS".

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