Micro-opto-mechanical beam deflectors

Steffen Glöckner
Rolf Göring
Torsten Possner
Fraunhofer Institute for Applied Optics and
Precision Engineering Jena
Schillerstrasse 1
D-07745 Jena, Germany
E-mail: gloeckne@iof.fhg.de

Abstract. The utilization of micro-optical 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 micro-optical components for efficient beam manipulation is quite small, high-speed actuators with small electrical power consumption can be used. We present a variety of micro-optical configurations and discuss their potential for the creation of different types of miniaturized scanners and switches. The combination of micro-optical components already available and semiclassical piezoelectric actuators leads to new types of switching and modulation systems for a very broad spectrum of applications. © *1997 Society of Photo-Optical Instrumentation Engineers* [S0091-3286(97)00205-5]

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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 are different micro-optical concepts existing for beam deflection and modulation.[1,2] Due to the small element dimensions of micro-optical components, very compact, fast, and low-energy consumption switches, scanners, etc., can be realized. The high flexibility of micro-optical components and systems can be used to build up well-matched solutions for a variety of switching and modulation purposes on the basis of different optical sources. However, a series of essential problems have to be still solved for future commercialization: Serious problems arise from the integration of the single micro-optical elements into an optical system due to the high positioning accuracy and, to some extent, the small dimensions of the components. It is not completely clear which actuator concepts are most suited for driving micro-optical components in scanning and switching systems. Up to now, piezoelectrical actuators have mainly been used, which are at least well suited with regard to their translational range. Consequently, there is a need for well-matched optomechanical concepts to be developed. Finally, some special development is also needed in the field of micro-optical technology, as the different applications of micro-optical beam deflectors impose certain limits on optical parameters (optical losses, cross talk, beam quality), which can be met only with appropriate parameters of the micro-optical components.

In this paper, we present a number of micro-optical concepts for steering coherent and incoherent beams. In Sec. 2 we discuss general aspects of micro-optical beam steering. Beam scanning systems for coherent beams, especially Gaussian beams, are presented in Sec. 3. In Sec. 4 we present a concept for deflecting incoherent beams emitted by multimode fibers and discuss some applications. Section 5 deals with aspects of system integration. Finally, we draw conclusions and discuss future work in this area.

2 General Aspects of Micro-optical Beam Steering

2.1 *Micro-optical Scheme*

In Fig. 1 a schematic diagram shows the micro-optical components that are necessary for a micro-optical beam deflector or scanner. The first element in the chain is the optical source. Therefore it is not surprising 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 Secs. 3 and 4. The central element is the beam-steering unit. The beam-steering unit comprises micro-optical elements as well as a convenient mechanical actuator. Therefore, the system is actually an opto-mechanical system. The postprocessing can be, e.g., a collimation, fiber coupling, or focusing onto a detector, working piece, etc. There are requirements on the:

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

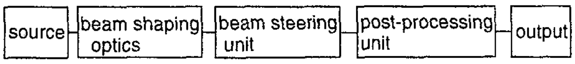

Fig. 1 Principle of a micro-optical beam deflector or scanner

- switching time and/or modulation rate.

The requirements that 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 made.

2.2 *Actuation Concept*

The actuation concept is a critical point for micro-optical 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 micro-optical components we use are from several tens of milligrams up to several grams in mass, so those actuators are too weak to be applied.[3–5] Many applications require switching times on the order of a few milliseconds, which can be realized by means of piezoelectrical actuators. Customary piezoelectrical stage actuators are stronger by far than required in our application. Thus, in order to create piezoelectric actuators matched to the movement of micro-optical components (in weight, displacement range, and speed), another concept has been investigated. Bimorph piezoelectric layers are attractive candidates to achieve movements of 100 μm and more. 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, which suppresses the motion in the unwanted direction. Figure 2 shows a planar and a cylindrical arrangement of such parallelograms, which is capable of two-dimensional motion. There is enough room for 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 lengths and stiffnesses have been realized with maximum displacements between 20 and 200 μm. Typical resonance frequencies are 0.1 to 0.6 kHz with switching times of a few milliseconds.

3 Deflection of Gaussian Beams

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

$$E_{\text{Gaussian}} = \pi^2 \omega_0^2 \theta_0^2 = \lambda^2 = \text{const.} \qquad (1)$$

E is a constant and is conserved during propagation through diffraction-limited optical systems. Due to the small etendue, 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, $2\omega_0 = 5$ μm gives $\theta = 0.1$).

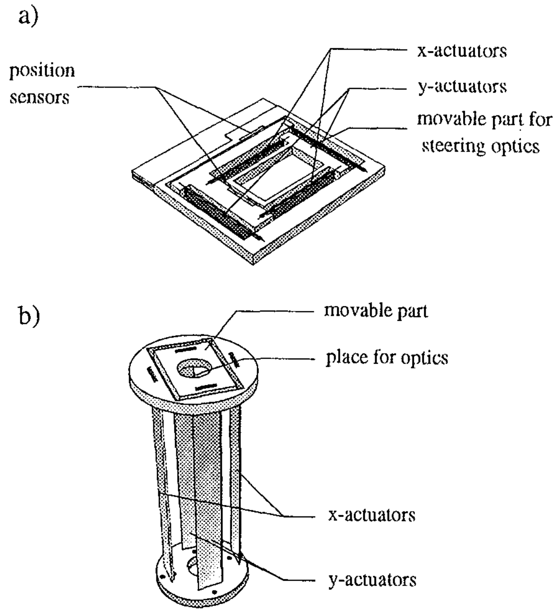

Fig. 2 Piezoelectric bending actuators for optical beam steering: (a) planar arrangement, (b) cylindrical arrangement

Therefore, a simple beam deflection concept can be realized by focusing the incoming beam with moderate numerical aperture and placing very simple micro-optical elements such as lenses, prisms, and mirrors in the focal plane of the focusing optics. The required mechanical displacements are on the order of 10 to some 100 μm 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, that can be resolved) can be defined as the ratio between the maximum deflection angle and a characteristic angle, which describes the divergence of the outgoing beam (see Fig. 3):

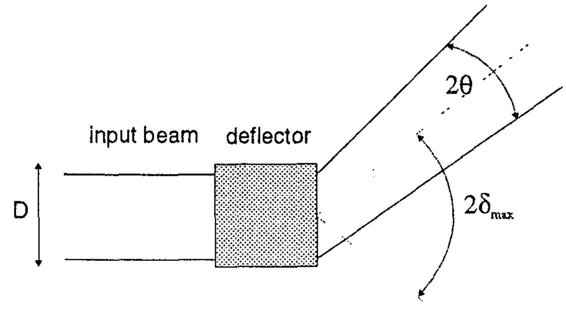

Fig. 3 Definition of beam-deflector resolution

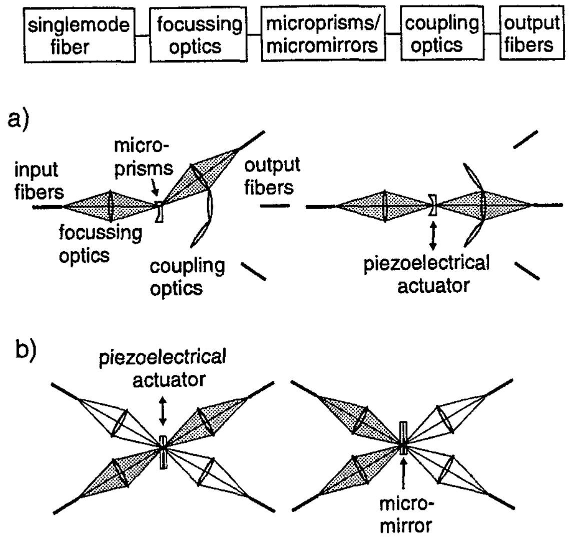

Fig. 4 Principle of a microoptical single-mode fiber switch: (a) 1×3 switch using microprisms, (b) 2 × 2 switch using micromirrors.

$$N=\frac{\delta_{\max}}{\theta}. \qquad (2)$$

Micro-optics offers high-resolution as well as low-resolution devices on properly adjusting the deflection angle and the divergence of the beam behind the deflector.

3.1 *Low-Resolution Scanners—Miniaturized 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 micro-optical concept of a single-mode fiber switch driven by a piezoelectric actuator. Switches for communication systems need excellent optical parameters (low insertion losses, low cross talk). The focusing onto the deflecting structure has to be diffraction-limited, in view of the need for cross talk reduction. The deflected beam is coupled into an output fiber with high efficiency by means of appropriately designed coupling optics. In theoretical investigations we could show that it is possible to achieve high coupling efficiencies (above 95%) using aspheric focusing and coupling optics with the microprisms being on a thin substrate, thus reducing the wavefront aberrations. In experiments, we used commercially available Schott-Hoya-aspheres for focusing and coupling, and we fabricated microprisms by anisotropic wet chemical etching in silicon, obtaining a master for subsequent replication into polymers. A beam emitted by a single-mode 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 deg. This results in a deflection angle of 18 deg. For that single-mode fiber switch, we obtained low insertion losses (<1 dB) and low cross talk between the output channels (<-50 dB). The wide-angle spectrum of the Gaussian beam is the reason for the remaining cross-talk. The switching time was around 1 ms. 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] A crossbar fiber switch with metal micromirrors embedded into two substrate layers gave similar results for the coupling efficiency, cross talk, and switching times.

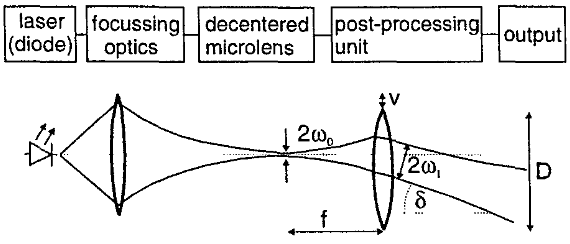

Fig. 5 Beam deflection with decentered, collimating microlenses.

With the help of Eq. (2) the resolution N is determined by the maximum deflection angle $\delta_{\max}$ [i.e., the prism angles in Fig. 4(a)] and the waist radius ω_0 of the laser beam in the focal plane:

$$N=\frac{\pi\omega_0}{\lambda}\ \delta_{\max}. \qquad (3)$$

For example, with $\lambda=1.55\ \mu$m, $\omega_0=5\ \mu$m, $\delta_{\max}\approx 30$ deg one obtains a 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 address single switching states. The number of output channels can be increased by using a two-dimensional arrangement of microprisms. It can be further increased by 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, $\delta_{\max}\approx 30$ deg 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.

3.2 *Scanner with Medium Resolution*

From Eq. (2) it is obvious that the resolution can be increased if the laser beam leaves the deflecting device in a collimated manner, i.e., with small divergence. This can be achieved simply by using a collimating lens that is decentered from the optical axis (Fig. 5). To avoid vignetting over a large diplacement range, the focusing lens has to produce, e.g., a magnified image of the laser (diode). The numerical aperture of the scanning lens is larger than the beam divergence in front of the scanning lens. The deflection angle δ is given by

$$\delta=\arctan\left(\frac{v}{f}\right). \qquad (4)$$

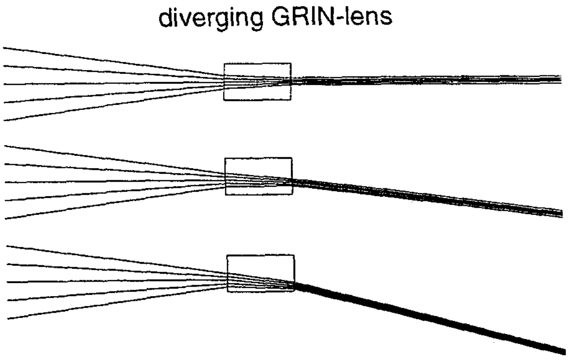

Fig. 6 Beam deflection with diverging GRIN lenses.

The focusing lens influences the resolution of the system, which is given by the maximum displacement $v_{\max}$ of the lenses and the waist radius ω_0 of the spot behind the focusing lens. The waist of the deflected beam is situated right behind the deflecting lens. The waist diameter of the deflected beam is $2\omega_1$, and $v_{\max}$ is given by $\pm(D-2\omega_1)/2$. The resolution is given by

$$N=\frac{v_{\max}}{\omega_0}=\frac{\pi\omega_1}{\lambda}\,\delta_{\max}. \tag{5}$$

Consider a system with $\lambda=780$ nm, $2\omega_0=5\ \mu$m, and $N=50$. This requires an actuator with a maximal displacement of $2v_{\max}=250\ \mu$m and a deflecting lens with an isoplanatic region of 250 μm, a focal length that achieves the desired deflection angle, and a numerical aperture sufficient to transform all the light that is incident on it. Since the focusing lens magnifies the laser spot (magnification M), it is sometimes more convenient to move the focusing optics instead of the deflecting lens. This will reduce the required displacements by a factor $1/M$.

High numerical apertures and large isoplanatic regions of the scanning lenses are required to deflect the beam with low losses and low wavefront aberrations. 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 large refractive index changes during the ion-exchange process, delivering lenses with large numerical apertures.

Figure 6 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 experiments the relation between deflection angle and displacement was measured.[7] For a typical cylindrical lens with a typical index profile and a thickness of 500 μm a deflection/displacement ratio of 0.43 deg/μm was measured for an incoming beam with $\lambda=0.67\ \mu$m and $\omega_0=2\ \mu$m.[8] The value of $\delta_{\max}$ was 30 deg, the maximal displacement was 140 μm, and the far-field divergence $\theta=0.9$ deg. This corresponds to $2\omega_1=27\ \mu$m and a resolution of $N=35$.

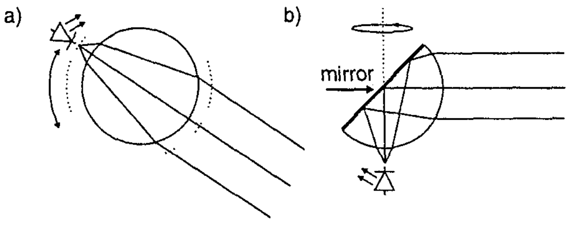

Fig. 7 Beam deflection with ball lenses: (a) laser moved on a circle, (b) rotating hemispherical lens.

As the beam-steering unit (Fig. 1) is an optomechanical system, some of the optical problems can be transferred to or from the actuator. Figure 7 shows a simple example. Ball lenses are attractive optical elements for beam steering. Because of their symmetry, the beam quality of the deflected beams does not change for different steer angles if the source is moved on a circle instead of a straight line. This can be realized by an appropriate actuation mechanism. In contrast, some problems of the actuation principle can be avoided choosing a more complex deflection optics. It is difficult to realize a two-dimensional motion without any cross talk of the mechanical axes of an actuator. This will also result in optical cross talk. In some applications, careful optical design will ensure that the mechanical cross talk does not destroy the optical performance even for high switching speed (e.g., the above-mentioned micro-optical single-mode fiber switch). In other applications the deflections in the two directions can be separated by introducing two steering optics, one for each direction. Therefore the mechanical axes are no longer coupled.

3.3 *High-Resolution Scanners*

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

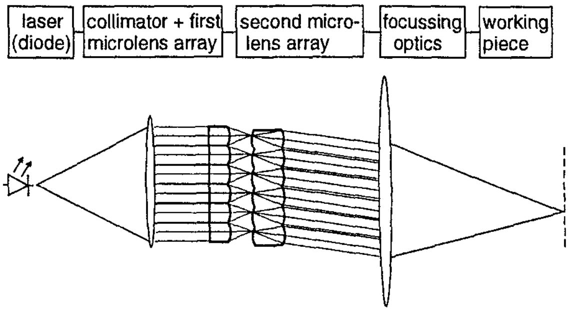

Fig. 8 Beam deflection with decentered microlens arrays.

Table 1 Summary of the concepts of micro-optical laser-beam deflection

Deflecting elements	Typical resolution (1-D)	Applications
Microprisms or micromirrors in convergent beams	5	Fiber switches
Decentered, collimating microlenses	20–300	Illumination systems, optical inspection, bar-code reading
Decentered microlens arrays	500–1000	Optical inspection, material processing, optical metrology

ings. The whole setup acts as a diffraction grating, allowing efficient beam steering to discrete angles only.[9,10] To achieve deflection angles of 10 deg 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 deg 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:

$$N=2\,\delta_{\max}\,\frac{d}{\lambda}. \tag{6}$$

In Table 1 the various concepts for micro-optical beam deflection are summarized.

4 Scanning of Incoherent Beams

The beam deflection concept depends strongly on the kind of the input beams. Incoherent beams cannot be focused with a single lens to spots of a few microns without large light losses. For instance, the etendue of a multimode fiber with core radius a and numerical aperture NA is given by

$$E_{\mathrm{MMF}}=\pi^2 a^2\ \mathrm{NA}^2 \gg \lambda^2 = E_{\mathrm{Gaussian}}. \tag{7}$$

The etendue is much higher than the etendue of a Gaussian beam. Therefore, displacements in the range of some 100 μm to millimeters are necessary to deflect the beam with conventional optics. This will increase the switching time to unacceptable values. For efficient manipulation of incoherent beams, lens arrays are required, resulting in a segmentation of the input beams. Generally, the same setup as in Fig. 8 can be used. A small spot behind each lenslet of an array is generated. The etendue of the single beams is reduced, and the single beams are spatially separated (Fig. 9). The reduction in the etendue of the single beams is given by

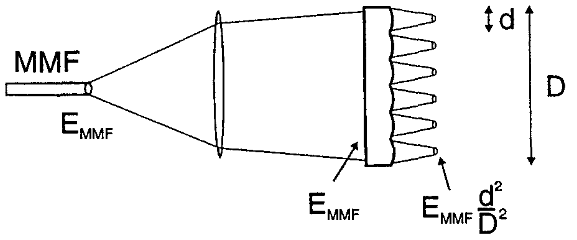

Fig. 9 Separation and etendue reduction of incoherent input beams with microlens arrays: E_{MMF}, etendue of the multimode fiber MMF; $E_{\mathrm{MMF}}d^2/D^2$, etendue of the single beams behind the lens array

$$\frac{E_{\text{sep beam}}}{E_{\mathrm{MMF}}}=\frac{d^2}{D^2}. \tag{8}$$

The spot size and the divergence of the beams can be adjusted by choosing appropriate focal lengths of the microlens arrays and the collimating lens. The single beams can now be manipulated efficiently in combination with small displacements. The coherence between the single beams is not destroyed if the focusing lens array and the manipulating element consist of coherent elements. Therefore the problem of the grating behavior 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.[12] 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 behavior 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 Fig. 10. The lenses are made of quartz with a lens pitch of 400 μm and an f-number of 5. The surface profile was spherical within 80% of the single lens. The lens arrays are commercially available from the German company LIMO. In front of the focusing array we realized a beam with $\lambda=670$ nm and a divergence of $2\theta=17$ mrad. The focused light was concentrated in a number of lines of 40-μm lateral dimension in the common focal plane of the arrays. The recollimated beam contained

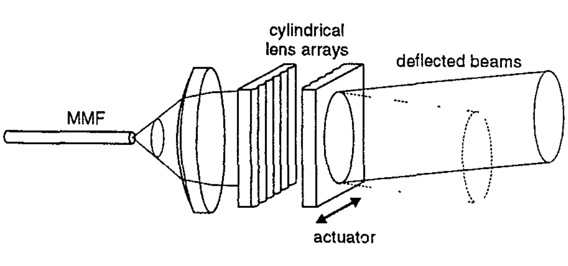

Fig. 10 Beam steering experiment with lens arrays in a confocal arrangement with incoherent illumination.

60% of the energy for the unsteered case. We could steer in one dimension up to ±5 deg with displacements of ±160 μm. 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 appeared and the efficiency was only 30%. The results can be improved by 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 suitable 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 addressed by fabrication technologies.

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

5 Aspects of System Integration

Almost all the concepts of micro-optical beam deflection presented here are based on transmissive optical elements such as lens- and prism-like structures. Contrary to on-chip solutions with tilting micromirrors, etc., there is no possibility of merging directly the micro-optical element and the microactuator. All the micro-optical elements used in the systems presented above exist initially 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, and special problems appear with the alignment of lens or prism arrays due to strong requirements on the orientation accuracy of these elements. Up to now, no standard handling and mounting techniques exist for micro-optical components. For stability and reliability reasons the systems discussed above should be made as compact as possible, and passive alignment approaches should be preferred. Figure 11 shows two examples of miniaturized fiber optic switches where these considerations have already been taken into account.

Polymer microprisms are replicated on a Selfoc® lens with quarter pitch, 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 single-mode fibers or multimode fibers with small core, an array of graded-index (GRIN) lenses can focus the beams onto the fibers. All elements are cemented together and give a very small device with a volume of a few cubic millimeters.

We build up configuration (a) in Fig. 12 with multimode fibers with a core diameter of 200 μm, a Selfoc® lens (H-1.8-0.25-0.63), and a metal fiber holder with 200-μm 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 greatly increased by using optimized optical components. For this system the etendues of the input and output fibers do not match, which results in beam degradation but allows for higher functionality, namely, possible switching to different fibers.

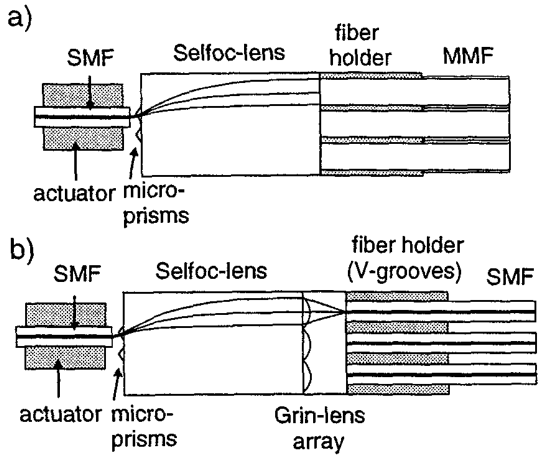

Fig. 11 System integration of a fiber switch: (a) single-mode fiber to-multimode fiber, (b) single-mode fiber.

Configuration (b) is a more sophisticated device with input and output fibers having the same etendue. To achieve sufficient optical parameters an optimization of the Selfoc® lens and the GRIN array has to be realized.

6 Conclusions

We have shown that a lot of micro-optical 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. For applications with Gaussian beams and moderate output beam requirements, standard micro-optical components such as Selfoc® lenses, ball lenses, and aspheres can be used as single elements, assembled to a defined system. Special nonstandard microlenses, however, must be used for optimum resolution. Special microprisms are attractive candidates for the realization of fiber optic switches with discontinuous beam deflection, where systems with negligible aberrations 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 micro-optical systems.

Acknowledgments

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Steffen Glöckner finished his diploma work in physics on micro-optical single-mode fiber switches at Friedrich Schiller University in Jena in 1995. He is now with Fraunhofer Institute for Applied Optics and Precision Engineering in Jena and works in the micro-optics group.

Rolf Göring, after finishing his diploma work in physics at Moscow State University, attended Friedrich Schiller University in Jena. Here he received the Dr.rer nat degree in 1981 after five years, work in the field of nuclear magnetic resonance investigations of glasses, metals, hydrides, and polymers After that, he worked in the field of integrated optics for several years Since 1992 he has been with Fraunhofer Institute for Applied Optics and Precision Engineering in Jena, as head of the micro-optics group

Torsten Possner received his diploma and Dr.rer.nat degree from Friedrich Schiller University in Jena in 1983 and 1989, respectively. There he was working in the field of integrated optics in glass. Since 1991 he has been with Fraunhofer Institute for Applied Optics and Precision Engineering in Jena. He is working in micro-optics, especially the fabrication of gradient-index lenses by ion-exchange processes.