Micro-optical Fiber Switch for a Large Number of Interconnects Using a Deformable Mirror

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***Abstract*—In this letter, we demonstrate the limitations for $1 \times N$ free space optical switch with a moving macro-lens. We use a deformable mirror to overcome these limitations. The adaptive mirror corrects for the aberrations. Power coupling efficiencies between 6 and 3 dB (including losses due to the optical elements) are feasible for an optical switch allowing up to 3019 receiver fibers.**

***Index Terms*—Adaptive optics, deformable mirror, micro-opto-electro-mechanical systems (MOEMS), optical switch.**

I. Introduction

DURING THE PAST few years, the demand for optical telecommunications has boomed [1]. In order to satisfy this demand, new optical switches are required to replace the electrical switches used up until now. Optical switches with a few interconnects (1×2, or 2×2) have been published for a couple of years [2]. Nevertheless, optical telecommunication networks need optical switches with large number of interconnects. Alignment tolerances, diffraction of the Gaussian beams, and aberrations are parameters which are more critical for optical switches with large number of interconnects than for optical switches with a few interconnects. Most of the published optical switches with large number of interconnects are using micromirrors with sizes in the range of 100–500 μm [3]–[5]. These switches have relatively small collimated beams, which in the case of two-dimensional (2-D) micro-electro-mechanical system (MEMS) optical cross-connect, limit their expandability due to diffraction [6]. Another approach (without micromirrors) is to use a macro-lens and have larger collimated beams. With this approach, the diffraction of the Gaussian beam is less critical, but aberrations become significant. To overcome this drawback, there are two possible ways. One is to use a diffraction-limited designed lens [7]. The other way, which we have chosen, is to use a conventional lens and correct for the aberrations using an adaptive mirror. In this work, $1 \times N$ optical switches are studied. Investigations are conducted to describe the physical properties of the switches and to determine their limitations. The merit function of optical switches is their power coupling efficiency. The limitations, mainly due to aberrations and misalignments of the optical components, are overcome using a micromachined deformable mirror.

Manuscript received August 22, 2001; revised November 6, 2001.

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Publisher Item Identifier S 1041-1135(02)01195-3.

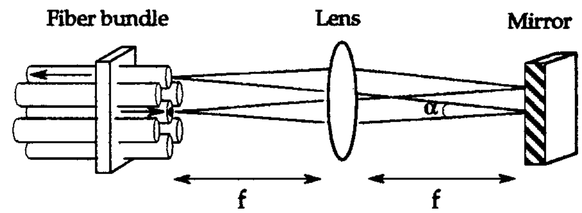

Fig. 1. Schematic setup of the free space optical switching system. The source fiber is imaged ($4f$ system) onto one of the receiver fibers by moving the lens laterally.

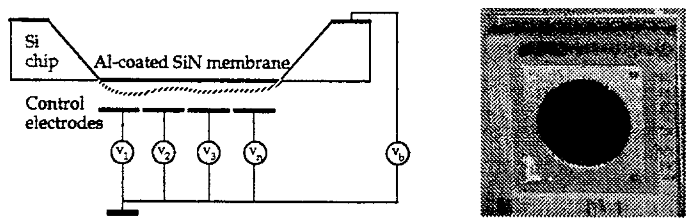

Fig. 2. Schematic and photograph of the micromachined deformable membrane mirror. The membrane has a diameter of 15 mm and a thickness of $d < 1$ μm. The surface of the membrane is coated with a 0.2-μm-thick reflective aluminum layer. Its active area has a diameter of 12 mm.

II. General Concept

The optical system has two functions. First, it images a single-mode source fiber onto another single-mode receiver fiber (coupling function). Second, it deflects the beam to address one of the receiver fibers (switching function). Fig. 1 shows the system composed of a fiber bundle, a lens and a mirror.

III. Description of the Deformable Mirror

We use a deformable mirror which is an adaptive membrane mirror fabricated by bulk silicon micromachining at the T. U. Delft [8] (see Fig. 2). Electrostatic deflection is generated by 37 electrodes disposed under the membrane in a hexagonal array. The maximum applied voltage is around 190 V. Since the membrane can only be deflected toward the electrodes, a bias voltage of $V_b \simeq 141\ V$ is applied to the membrane to achieve bidirectional movement. The produced deflection corresponds to a concave mirror with a focal length of about 2 m. The initial setup is made to compensate this slight defocus. The membrane mirror has the capability to efficiently correct the first 15 Zernike polynomials. The optimization of the shape of the membrane for maximum power coupling efficiency of each connection is obtained with the help of an evolutionary algorithm [9]. It can be described by the following operations: reproduction, mutation,

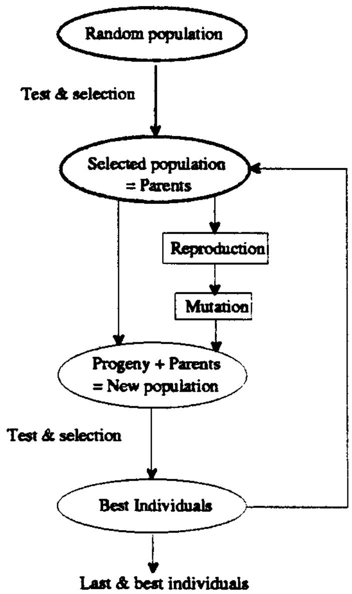

Fig. 3. Genetic algorithm based on the Zernike modes of the membrane. A population is randomly chosen and tested. The best individuals are selected for reproduction, their genetic codes are mixed to create a progeny. The progeny undergoes a mutation, some Zernike polynomial weights are randomly changed. The progeny is tested and compared to their parents. The best individuals are kept for a new reproduction. Each reproduction is considered as an iteration.

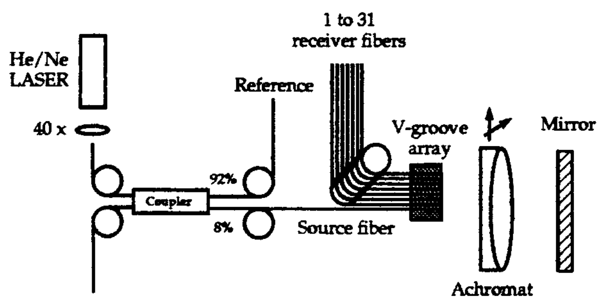

Fig. 4. Experimental setup of the switching system.

competition, and selection. In our model, each possible shape of the mirror is an individual. This individual is described by the weights given to the first 15 Zernike polynomials to deflect the membrane. The weights given to the polynomials are the genetic code of the individual. Fig. 3 shows the block diagram with the main steps of the algorithm. The maximum efficiency is usually obtained after less than 20 iterations.

IV. Experimental Setup

The experimental setup is schematically shown in Fig. 4. Light emitted from a He–Ne laser ($\lambda = 633$ nm) is coupled into a single-mode fiber (SMF) using an aspheric lens. A 92%/8% coupler splits the signal into a reference fiber and a source fiber. The source fiber is part of a linear array of 32 SMFs. The 32 fibers are held in a commercially available silicon V-groove array. The distance between adjacent fiber cores is 250 μm$\pm$0.5 μm. The SMFs have a cutoff wavelength of 590 nm. The mode field diameter is $2w_s = 4.5$ μm, corresponding to a core diameter of 3.8 μm and a numerical aperture of $NA_{\rm fiber} = 0.11$. The cladding diameter is 125 μm. The linear array of fibers is placed in the front focal plane of

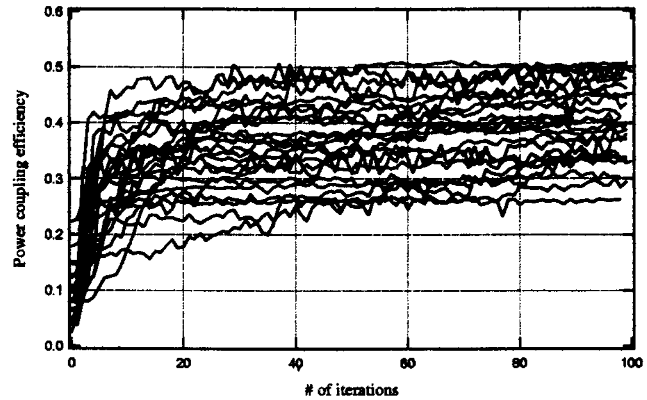

Fig. 5. Power coupling efficiency optimization curves for most of the 31 configurations.

the lens, whereas the mirror is placed in the back focal plane. The lens is an achromat of focal length $f = 40$ mm with an antireflective coating (reflectance $< 0.3\%$). The achromat is a commercially available doublet (Linos # 322 209) made of SF2 ($n = 1.64$ at 633 nm) and BK7 ($n = 1.52\%$ at 633 nm). Switching from the source fiber to any of the 31 receiver fibers is possible by moving the achromat laterally using a precision x–y stage with a resolution of 0.14 μm and a speed of 80 μm/s. The signals from the receiver fiber and the reference fiber are detected with calibrated silicon photodiodes. The ratio of the receiver and the reference signal gives the coupling efficiency. The way we use the linear array of fibers, the source fiber at one end demonstrates the feasibility of a system which is twice as large with symmetric displacement of the achromat. The 32 fiber linear array can, therefore, demonstrate the feasibility of a 1×62 one-dimensional (1-D) system. Moreover, 2-D arrays of fibers can be switched if the achromat is displaced in both x and y directions. The 32 fiber linear array can, thus, demonstrate the feasibility of a 1×3019 2-D system.

V. Results

In general, after ten generations, the algorithm has converged (see Fig. 5). The important parameters to get good convergence are the amount of mutations, as well as the number of modes used. Fifteen to twenty modes are enough for the optimization. If less than fifteen modes are used, the optimization is not optimal. With more than twenty modes, the algorithm gets slower without a significant improvement of the result. It is not astonishing that the number of useful modes is in the 15–20 range as it corresponds to the aberrations up to the sixth order (secondary aberrations). The optimization time is several minutes. However, each connection has its own optimized deformation which can be memorized, storing the voltages applied on each electrode. With these preset values and thanks to the good repeatability of the deformation of the membrane [10], the optimized deformation can be recalled for later connection to the same receiver fiber. Experimentally, no significant decrease of the coupling efficiency was measured in recalling specific deformations. Fig. 6 shows the coupling efficiency of our system using the deformable mirror, compared to the same system with a conventional flat mirror. The

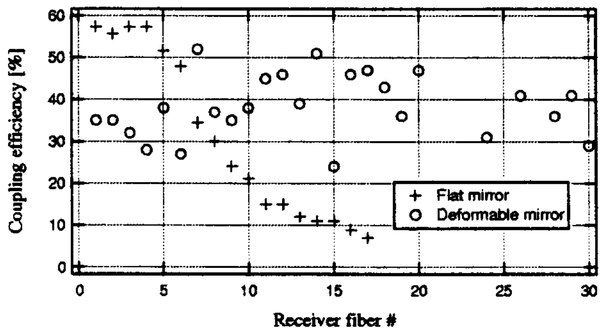

Fig. 6. Measured coupling efficiency using a deformable mirror compared with a flat mirror.

flat mirror system has a rapidly decreasing power coupling efficiency with the increasing number of receiver fibers. For comparison, the optimized power coupling efficiency using the deformable mirror is between 25% and 51% for all fibers and shows no fading with increasing fiber number. The measured crosstalk is less than -30 dB (detection limit). The total loss due to the optical elements is estimated to be 22%, by considering two interfaces between the receiver fiber and air with 4% Fresnel losses each, 1% transmission loss inside the achromat, and 0.3% of reflectance at both interfaces and a reflectivity of 87% for the mirror. The difference between the maximum coupling efficiency (78%) and the measured ones (51%) has several reasons. First, the mirror we used has a large astigmatism at rest, because of residual stress in the membrane. Simulations show that an astigmatism of $\lambda/5$ leads to a decrease of the coupling efficiency by 50%. The measured deviation of the membrane from the perfect plane corresponds to $3\lambda - 4\lambda$ at rest. 4λ corresponds to a quarter of the correction range of the mirror. Although the mirror has the potential to correct its own imperfections, this limits the ability to further correct the system aberrations. A second point limits the performance of the mirror: the instability of the voltage supply. Fluctuations have been measured which lead to deformation fluctuations of 0.1 μm ($\cong \lambda/6$) at the center of the membrane at maximum voltage $V = 190$ V.

VI. Conclusion

We have shown how a deformable membrane mirror can correct the aberrations of an optical switching system. The measured coupling efficiencies for connections up to the 31th receiver fiber of a 1-D one-directional system are found to be between 25% and 51% (including the 22% losses due to the optical components). Compared to an optical system without correction of the aberrations, the system with the deformable mirror is better for connections beyond the eighth receiver fiber (see Fig. 6). We have demonstrated the feasibility of a 1-D one-directional 1×31 optical switching system, which corresponds to a 1×3019 2-D system. The limit is given by the size of the achromat and its lateral displacement required for the switching. A larger achromat (with a larger focal length) and a larger deformable mirror should be able to address more receiver fibers. The correction of aberrations was limited in our experiments by the residual stress of the membrane. Deformable membrane mirrors with almost no stress have been reported [8] and would improve the coupling efficiency by around 10%. Because of the hexagonal geometry of the electrode structure, some types of aberrations can be corrected more easily than others. For example, the secondary astigmatism (or ashtray) is particularly well adapted to be corrected by a hexagonal structure of electrodes. In contrary, the spherical aberration is more difficult to correct, since the center part of the membrane has to be pushed and a circular ring has to be pulled. A circular structure of electrodes would be more adapted for such a deformation. Deformable membrane mirrors with different electrode structures are commercially available [11] and show the feasibility of such improvements. Finally, the use of IR light ($\lambda = 1.55$ μm) instead of red light ($\lambda = 0.633$ μm) would not generate different results. It would only relax the alignment tolerances, as the diameter of the core of SMFs is around 10 μm for $\lambda = 1.55$ μm and around 4 μm for $\lambda = 0.633$ μm.

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