Massive free-space optical 1xN fiber switch using an adaptive membrane mirror

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ABSTRACT

We present a 1xN switch for single mode fiber optical communication systems, which is composed of an array of fibers, an achromatic lens, and an adaptive membrane mirror. The working principle of the optical switch is as follows: the center fiber of the array delivers the input signal, this signal is collimated by the lens, back reflected on the membrane mirror and refocused by the lens to an other fiber. The addressing of the receiving fiber is made by lateral displacement of the lens. However, using the achromatic lens under off-axis conditions introduces aberrations, which cause coupling losses to the receiving single-mode fibers. The deformable membrane mirror is used to adaptively correct these aberrations. The optimization of the coupling efficiency is made with the help of a genetic algorithm. For each position of the lens, the optimized voltages on the electrodes of the membrane mirror can be stored during the calibration procedure and afterwards recalled during operation of the switch. A demonstrator has been set up with a commercially available linear array of 32 single-mode fibers disposed in V-grooves, an achromatic lens mounted on a two-dimensional translation stage, and a membrane mirror made of silicon nitride coated with aluminum and electro-statically activated by thirty-seven electrodes [1]. To demonstrate the capabilities of the aberration correction we used the first fiber in the array as input fiber and optimized the coupling efficiency to all the other fibers in the array. We obtained insertion losses of less than 3 dB and a cross talk below 30 dB. These results prove the feasibility to build a switch with a two-dimensional array of more than 1000 addressable fibers.

Keywords: Deformable mirror, membrane mirror, adaptive optics, fiber switch, optical MEMS

1. INTRODUCTION

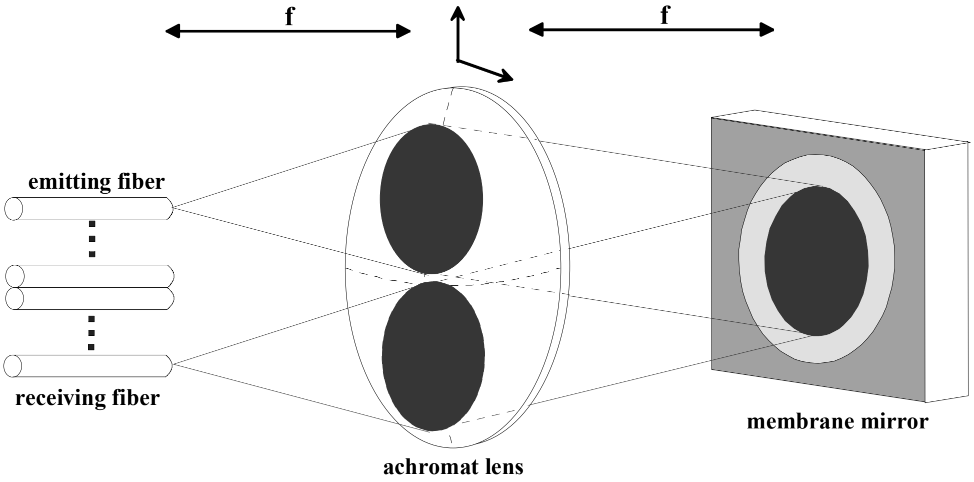

Figure 1: The concept of the fiber switch (with a 1 dimensional fiber array)

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An important increase of the optical telecommunications in size and transport capability has occurred during the nineties. The replacement of the electronic switches by optical switches has become obligatory. This is the reason why optical switches with the help of optical Micro-Electro-Mechanical-Systems (MEMS) have been developed recently [1]. The growing application of fiber optic local networks produces a need for even larger fiber switches [2]. We propose an original concept for a single mode fiber switch, which is shown in Fig.1. It is a 1xN fiber switch composed of an array of fibers, a lens and a deformable membrane mirror, which is fabricated following the optical MEMS technology and has been developed at T.U. Delft [3]. The array of fibers is placed in the front focal plane of the lens, whereas the deformable mirror is placed in the back focal plane. Switching from one fiber connection to another is possible by moving the mirror on the lateral direction. Using the deformable membrane mirror gives the ability to correct adaptively the aberrations and to optimize the coupling efficiency individually for every position. After the calibration procedure, which records the lens position and the optimized membrane mirror shape for each interconnection, we are able to automatically switch from one fiber to another.

2. EXPERIMENTAL SET-UP

The experimental set-up is presented in Fig. 2. A photograph of the main parts of the breadboard is shown in Fig. 3. A He-Ne laser is used as light source. It is injected into a single mode fiber connected to a 92%/8% coupler. The 92% output is used as a reference and the 8% output is connected to the input fiber of the switch. The switch is composed of 32 fibers disposed in an array of V-grooves made of silicon. The first fiber of the array is used as the input and the other 31 are the output fibers. The cores of the fibers are spaced by 250 µm ± 0.5 µm. The fibers are parallel within ± 0.1°. The achromatic doublet has a focal length of 40 mm. It can be moved with two step motors in the x and y direction to switch from one fiber to another. The speed of the switch is limited in this version by the speed of the step motors, the maximum deflection frequency of the membrane being 1 kHz

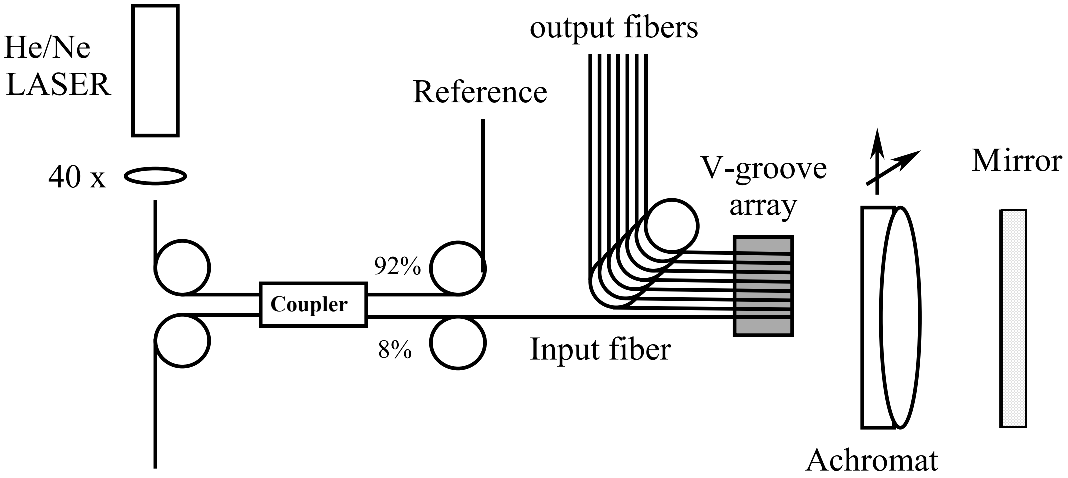

Figure 2: Breadboard set-up of the fiber switch (with a 1 dimensional fiber array)

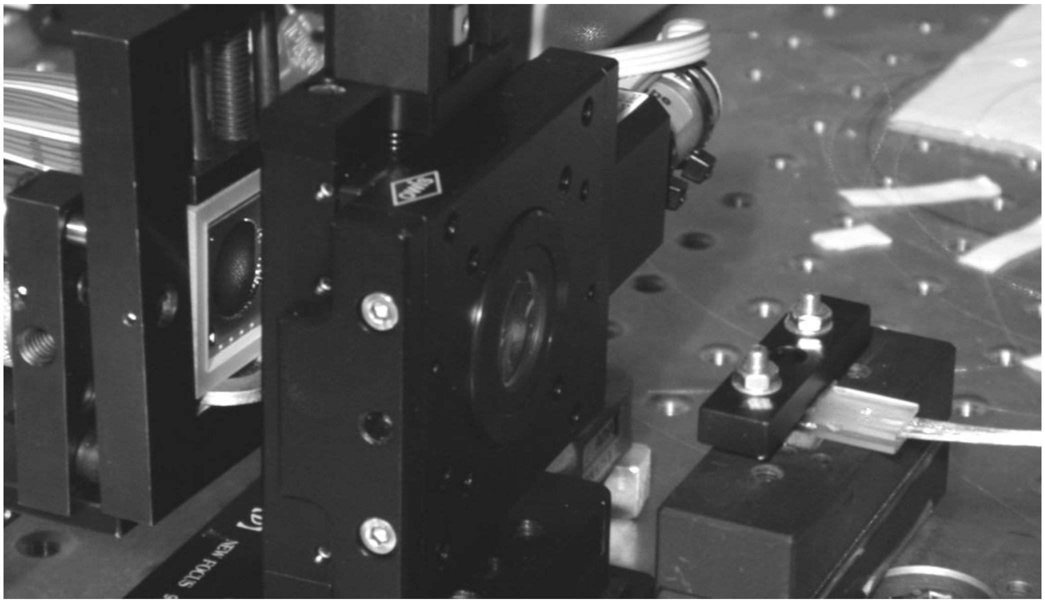

Figure 3: Photograph showing the breadboard of the 1D fiber switch

3. THE MEMBRANE MIRROR

The membrane mirror is aluminum coated, has a diameter of 15 mm, an active area of 12 mm in diameter and is electrostatically activated by 37 electrodes. The maximum voltage applied to the electrodes depends of the membrane and is around 200 V. The membrane mirror is driven by an analog to digital converter card of 12 bits controlled by a Pentium II PC. The membrane mirror can only be deflected in one direction and the maximum deflection is around 10µm. A bias voltage is applied to produce a deflection at half distance, which gives a concave mirror of about 2 m of focal distance. The switch is aligned to compensate this defocus. To correct the aberration, the membrane deformation is modulated around this bias position. Unfortunately, the membrane mirror used for this experiment has a strong initial astigmatism corresponding to 4 fringes at 633 nm, as shown in Fig. 4. This initial aberration of the mirror will influence the final result of the coupling efficiency. The optimization of the membrane deformation for each interconnection is made with the help of an evolutionary algorithm

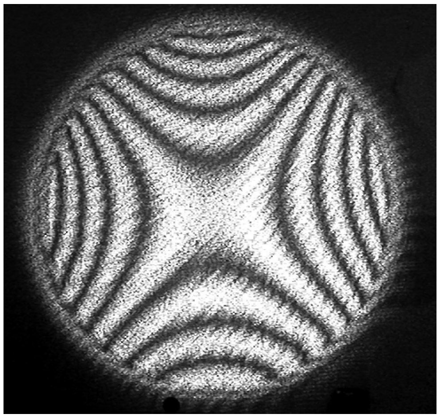

Figure.4: Interferogram of the membrane mirror showing the initial astigmatism

4. THE EVOLUTIONARY ALGORITHM

Evolutionary algorithms have been developed and used for many applications since the end of the fifties [4] [5]. These algorithms follow the principle of the evolutionary theory of the neo-Darwinian paradigm. The different steps of the algorithm are the following: reproduction, mutation, competition, and selection. We consider in our model each possible shape of the mirror as an individual. Each individual can be described by a set of electrode voltages, which is called the genetic code. We have to remember that the membrane deformation is driven by 37 electrodes wit a 12 bit DAC card, which means 4096 least significant bits per electrode. The full membrane deformation population is then $4096^{37} = 4.55.10^{133}$. It is impossible to test all these deformations; therefore, the evolutionary algorithm is most adequate in this case.

The block diagram of the algorithm is shown in Fig. 5. A random population is designed and tested. The best individuals of this population are selected for the reproduction. The reproduction is made by mixing the genetic code of the selection to create a progeny. During the mixing, a small part of the genetic codes undergoes a mutation, which is a random change of some codes. The obtained progeny is tested and compared with its parents. The best individuals from the comparison are selected to become the new parents. After several iterations the best optimization is obtained. We start with a random population of 500 individuals, the 10 best are selected to create the progeny in the following manner: the 3 best individuals create 20 children and the 10 best creates 70 children, theses 90 children undergo a mutation and are compared to the 10 parents. The 10 best individuals from these 100 individuals become the new parents. 1% of mutation is made on the first group of children and 10% is made on the second group. An iteration of this algorithm contains 100 deflections.

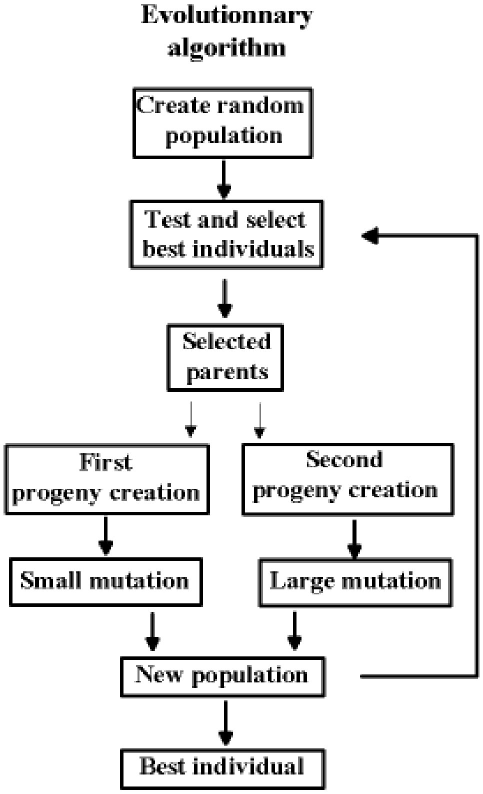

Figure 5: Block diagram of the evolutionary algorithm

5. THE RESULTS

The Fig. 6 shows the optimization of the coupling efficiency for fiber number 16 using the evolutionary algorithm. Most of the increase of the coupling efficiency is obtained with the first 20 iterations and after 60 iterations the maximum is achieved. It means that we obtained a full optimization after the test of less than 6000 deformations. For this example, the optimization starts at a coupling efficiency of 9% and the obtained maximum efficiency is 46%.

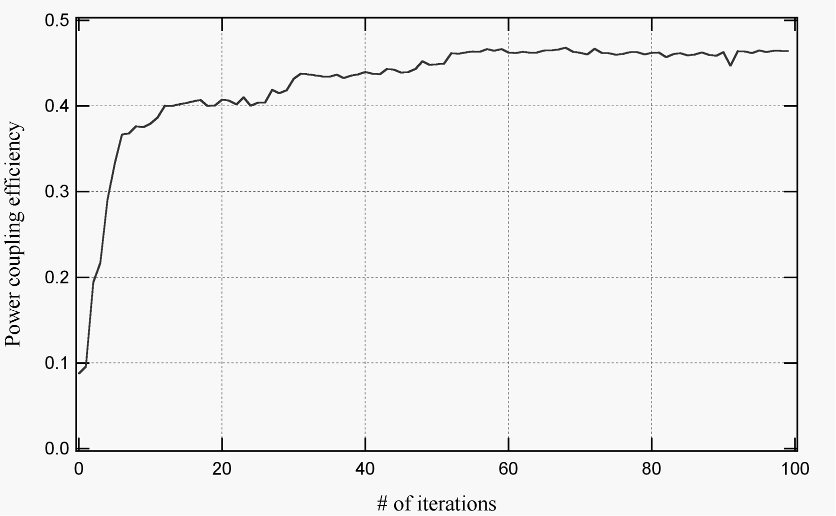

Figure 6: Optimization of the coupling efficiency vs. number of iterations

Figure 7 shows the coupling efficiency obtained for the 30 fibers within the array, using the first fiber as the input. We made a comparison between the measured coupling efficiencies for a flat mirror (96% reflectivity) and the maxima obtained with the adaptive membrane mirror (87% reflectivity). We see that the coupling efficiency for a flat mirror decreases rapidly with increasing distance between the fibers to be connected. The experimental results for the flat mirror follow quite well the theoretical curve obtained by simulation with a ray tracing program (ZEMAX$^{®)}$, taking into account the estimated 14% total losses due to the optical elements [6]. The coupling efficiency is less than 40% for the fibers beyond number 7. Compared to this, we see that with the help of the adaptive membrane mirror the coupling efficiency remains high for all fibers. A best coupling efficiency of 52% has been obtained on some fibers and the average coupling efficiency on all fibers is 39%.

We believe that the comparably small measured average coupling efficiency with the membrane mirror is mainly due to the strong initial aberration of this mirror. As calculated by a ray tracing analysis (ZEMAX$^{®}$), we can expect better performance with a membrane mirror having an initial astigmatism smaller than one fringe, which is technologically feasible. We verified also the calibration concept for the system. We optimized the coupling efficiency for fiber number 15 and stored the corresponding electrode voltages of the membrane mirror. Coming back to the same position after addressing other fibers, we got with the stored values for the electrode voltages the some coupling efficiency as before, which proves the reproducibility of the membrane mirror.

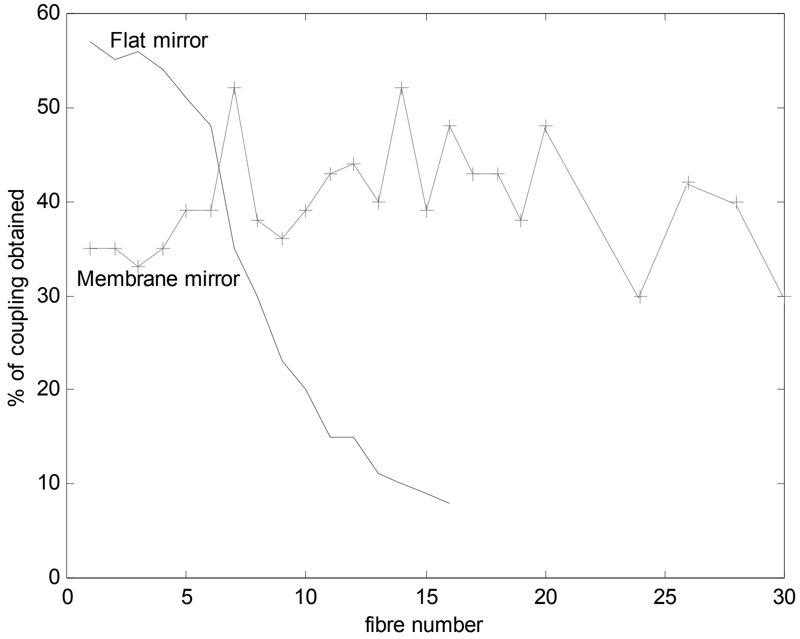

Figure 7: Measured coupling efficiencies vs. fiber number (input fiber number 1).

CONCLUSION

We proved the possibility to obtain a massive fiber switch with an insertion loss of less than 3 dB. Better performance than the investigated breadboard can be expected with a membrane mirror having smaller initial astigmatism and reduced losses introduced by the optical elements. We believe that switches with less than 50% (3 dB) insertion loss for as many as 30 fibers in one linear direction are feasible.

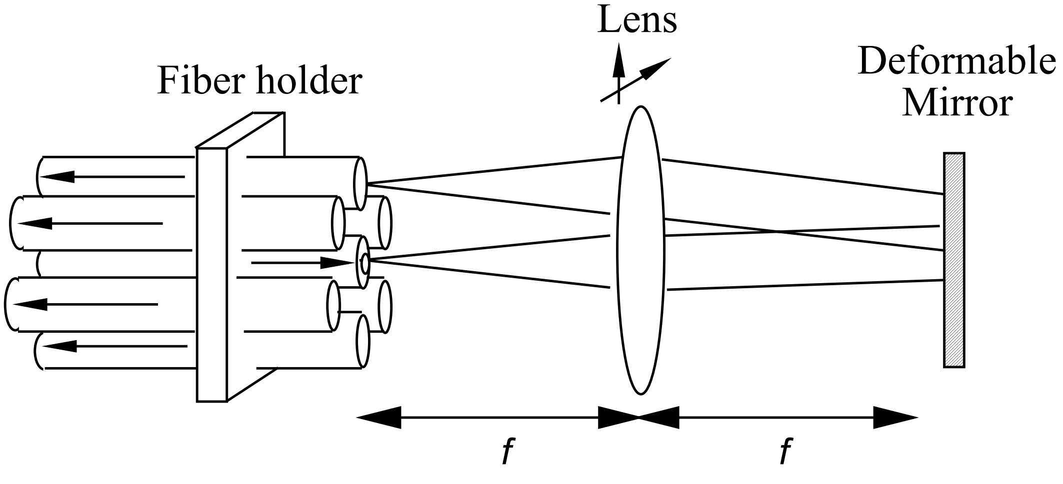

Figure 8: Massive 1xN fiber switch with 2-D fiber array

The presented breadboard can be transformed into a 2-D fiber switch as shown on the Fig. 8. Such a system would hold more than $\pi \cdot 30^2$ fibers. Therefore a 1x1000 fiber switch is feasible. The size of the switch is limited by the size of the lens and of the membrane mirror. We can imagine a fiber switch even larger with appropriate components.

ACKNOWLEDGMENT

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