A mio padre: la persona più geniale che ho incontrato

моя дружина

без тебя не

можливо

Ai due più grandi risultati ottenuti in questi tre anni

Sofia e Giulia

A Enrico che più di tutti ha amato la scienza
Summary

The thesis reports the results I have obtained in the adaptive optics (AO) fields during the PhD period. Working in the development of AO devices I received the opportunity of working in scientific and technological areas apparently different within themselves. It has been amazing to realize that adaptive optics can bring strong advantages to so far disciplines.

The thesis’s chapters are dedicated to different topics. The reader will notice that each of them is structured in a preliminary discussion of an adhoc technological development of application specific AO systems and in a second part devoted to its application.

The subject of the thesis are the deformable mirrors (DM). Two different technologies have been studied and developed: the firsts three chapters talk about membrane electrostatic DMs, and the last one about piezo bimorph mirrors. It is interesting to notice how each single application for being successful requires DMs technology specifically developed.

The list applications I have been working on are:

- Visual optics (chapter 1),
- Free space optics communications (chapter 2),
- Ultrafast laser pulse compression (chapter 3),
- Fast focalization with ultrafast laser (chapter 4).

The topics of the firsts two chapters are pretty industrial application while teh lasts two chapters are on scientific applications.
I would like to underline that this thesis gave me the possibility of working with two of the most important research institutes of the world in the field of ultrafast lasers. The activity of pulse compression carried out in collaboration with the ULTRAS laboratory of Milan, which has been for years and it still is, the owner of the world record of shorter artificial events ever realized by the human being (130 attosecond). Moreover the activity of the focalization with fast optics, has been carried out, at the Central Laser Facility of the United Kingdom. This facility has been the author of the laser Vulcan which is the most powerful in the world. It is been an honor for me working with some of the most famous scientists in this field: prof. Paolo Villoresi, Giulio Cerullo, John Collier, Chris Hooker and Andrea Cavalleri.
Sommario

La tesi riporta i risultati maggiori che ho ottenuto nel campo dell’ottica adattiva durante il mio percorso di ricerca del dottorato. Lavorando nello sviluppo tecnologico di questa disciplina ho avuto l’opportunità di accedere allo studio di aree della scienza e della tecnologia in apparenza molto distanti ma che in realtà sono legate dai benefici avuti nell’utilizzo di sistemi adattivi.

I capitoli della tesi sono divisi in modo da trattare separatamente applicazioni diverse. Leggendo la tesi il lettore noterà che vi è anche una divisione trasversale degli argomenti, ogni capitolo infatti è suddiviso in una parte di sviluppo tecnologico ad hoc per l’applicazione specifica a cui il capitolo fa riferimento e in una parte applicativa del dispositivo.

La tecnologia oggetto della tesi è quella degli specchi deformabili. Questi sono stati utilizzati nella loro versione elettrostatica nei primi tre capitoli e nella realizzazione bimorfa nel quarto. È interessante notare come ogni applicazione studiata richieda una tecnologia sviluppata su misura e con caratteristiche specifiche diverse da quella usata nelle altre applicazioni.

Le applicazioni su cui ho lavorato sono:

- ottica visuale (capitolo 1),
- comunicazioni ottiche in spazio libero (capitolo 2),
- compressione di impulsi laser ultrabrevi (capitolo 3),
focalizzazione con ottiche veloci di impulsi ultrabrevi (capitolo 4).

E’ facile notare come la prima parte della tesi riguardi applicazioni industriali (capitolo 1 e 2) mentre la seconda parte riguardi applicazioni prettamente scientifiche (capitoli 3 e 4). Voglio sottolineare come sia stato un grande onore per me partecipare alle attività scientifica della tesi in collaborazione con due dei migliori istituti di ricerca del mondo nel campo degli impulsi ultrabrevi. In particolare l’attività di compressione degli impulsi è stata svolta in collaborazione con il gruppo ULTRAS di Milano che è tuttora, ed è stato per anni, il detentore del record dell’evento artificiale più breve mai generato dall’uomo (attualmente circa 130 attosecondi). L’attività di focalizzazione con ottiche veloci l’ho invece svolta alla Central Laser Facility nel Regno Unito. Questa facility è autrice del laser Vulcan, il più potente mai creato, e sta terminando in questi giorni lo sviluppo del laser Gemini, il laser ad impulsi ultrabrevi con maggiore energia. E’ stato inoltre un grande onore poter lavorare con i più grandi specialisti di quel campo come i prof. Paolo Villoresi, Giulio Cerullo da Milano e i Dott. John Collier, Chris Hooker e Andrea Cavalleri nel Regno Unito.
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Introduction

Adaptive optics (AO) components are nowadays used in several applications. Medicine, industry, astronomy, lasers and science use AO components for improving their performances, playing on the flexibility given by these devices. It is worth to recall that AO is a branch of Photonics developed about 20 years ago. Its first application was in Astronomy, in terms of deformable mirrors for the correction of the image degradation induced by the atmospheric turbulence on ground telescopes. Since then, several techniques for correcting the aberration and the turbulence effect have been developed in either civil or military worlds. However, the number of users was initially very small and consequently the unit costs were very high. The first installations of AO mirrors were made in large scale facilities where budgets were compatible with the hardware high costs (both corrector and sensor). However thanks to research efforts the technology has improved and adaptive optics loops are now commercial products available to middle scale laboratories. Within the last decade, adaptive optics has been demonstrated to be successful in laser pointing correction and optical tweezers. This has been contributing to initiate a process of production and distribution of standard components. Nowadays AO is a very powerful technique for several applications and with an economical important perspective. However this evolution
has not yet brought to a breakthrough of AO in both scientific optical tools or in devices for large markets.

Each own manufacturer has for example its own method for building electrodes and materials for the mirrors. The AO, even if in principle powerful, do not have the deserved space in Science and technology because often the applications require better performances and higher damage thresholds. Moreover the most of the configuration are based on high voltage drivers which increase the cost of the device and make difficult reduce its size. From this, it clearly appears that AO technologies are not mature and that the definitely winning composition of materials, design and technique has not been found yet.

Moreover AO in science has contributed to numerous successful experiments. In most of the cases the use of AO has been seen as an instrument for touch-and-go experiment to be used just when crucial for getting the result or, in some other cases, the use of AO was considered as demonstrative experiment by itself.

In this framework clearly appears that for being effective AO device must be designed and tailored for each specific application.

I report some experiments in which AO has been used successfully after a carefully design of the devices.
Chapter 1. Visual Optics

1.1 Introduction

This chapter is dedicated to visual optics. The arguments discussed are two: the first section is dedicated to the development of an improved technology for membrane deformable mirrors, the second to the application of the deformable membrane mirrors to a fundus camera setup. Next step in the development will be the use of the new mirror object of section 1.2 in the fundus camera.

1.2 Push Pull membrane mirror for adaptive optics1*

Membrane deformable mirrors have a widespread diffusion in several applications. Comparing to other common devices for adaptive optics, such as liquid crystal modulators, bimorph mirrors, thermal mirrors, they have a lot of advantages: low cost, large dynamic behaviour, achromaticity, no hysteresis, relatively high optical load, good performance in aberrations generation, low power consumption. The drawback of these devices is the limited amount of maximum stroke and the high correlation within the electrodes. Silicon nitride membrane mirrors proposed by

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Vdovin and Sarro\textsuperscript{1} have good properties in terms of initial flatness and maximum stroke. The application of deformable mirrors play an important role in visual optics for the correction of the eye aberrations. Literature shows that membrane mirrors can be used in visual optics obtaining good results\textsuperscript{2,3}. Dalimier and Dainty\textsuperscript{4} showed a comparison within adaptive optics mirrors from different technologies. The results show that membrane mirrors, despite their advantages, do not have enough optical power to completely compensate eye aberrations. The improvement of membrane mirrors is still an open challenge. Recently Kurcinski\textsuperscript{5,6} has obtained higher strokes decreasing the membrane stress and applying a large transparent electrode on the top of the membrane. These important results still need of improvements in the fabrication techniques in order to reduce the stress on the membrane during the mounting that affects significantly the initial flatness. Furthermore new technologies are under development in membrane deformable optics. For example liquid mirrors based on electrocapillary or electromagnetic membrane deformable mirrors seem to be promising techniques for push-pull motion of the electrodes\textsuperscript{7}.

We propose an improvement in the electrostatic membrane mirror fabrication to obtain push-pull capabilities by the application of additional electrodes over the upper side of the membrane. Ten electrodes were added in the prototype here presented, one of these is realized with an indium-tin-oxide (ITO) coated glass to guarantee high transparency and electric conduction. Hence, the membrane is deformed by the non-transparent electrodes placed on its bottom side and, on the top side, by an external ring of nine electrodes and by the transparent one in order to add more stroke, improve the aberrations generation and to allow the use of the mirror without biasing the membrane\textsuperscript{6}. The performances of this push-pull mirror are compared to those obtained using a normal membrane mirror with only pull capability\textsuperscript{8}. The mirror design is studied by the solution of the Poisson equation\textsuperscript{9}. The comparison has been carried out using the approach of Dalimier and Dainty for the test of new mirrors\textsuperscript{4} observing both the capabilities in the generation of Zernike polynomials and, for visual optics, in the generation of 100 aberrated eye following the statistics published by Castejon-Mochon\textsuperscript{10}. The generation was
carried out in open loop by the measures of the displacement of each single actuator.

1.2.1 Push Pull mirror device

The device is composed by a nitrocellulose silver-coated membrane tensioned over a circular frame with a 25-mm diameter. The thickness of the membrane is 5 μm and the diameter of the useful area of the mirror is 10 mm. A schematic of the device is shown in Fig. 1.1.

Thirty-seven non-transparent electrodes are placed on the bottom side of the membrane and shaped as circular sectors. The electrodes are placed in three complete circular rings: one in the inner, six in the second, twelve in the third and eighteen in the outer for a total of 37 actuators, as shown in Fig. 2(a). Each of the electrodes has the same geometrical area. The distance between the membrane and the printed circuit board is about 70 μm. The spacer is calibrated in order to obtain a maximum deflection of about 6 μm. The electrodes are deposited on a diameter of 15 mm.

The presence of electrodes on only one side of the membrane gives a deformation capability in one direction, i.e. the distance between membrane and electrodes decreases applying voltages to the electrodes themselves. Such a device is then defined pull mirror.

Push-pull capability is obtained placing additional pads over the top side of the membrane. Nine non-transparent electrodes are faced to the outer ring of the lower electrodes and a circular transparent electrode is placed on the centre of the membrane and faces the first three inner rings of the lower electrodes see (Fig. 1.2). The electrical connection of the ITO-coated glass with the external amplifier is obtained by gluing a 5-μm Al-coated Mylar film. The ITO layer is deposited on a float soda lime 1-mm-thick glass. The thickness of ITO is 150 nm with a surface resistance of 12 WΩ/ and a transmittance of 89%.
Fig. 1.1. Schematic of the push-pull mirror and picture of the prototype.

Fig. 1.2. Geometry of the actuators: a) non-transparent electrodes placed under the bottom side of the membrane; b) transparent actuators placed over the top side of the membrane. The red line indicates the size of the membrane. The ITO coated glass is the dashed blue pattern.

Fig. 1.3 shows the interferogram on the active area obtained with no voltages applied on the actuators. The rms deviation is 29.8 nm, that is about $\lambda/20$ @633 nm, that is mainly caused by the surface flatness of the glass disc.
Fig. 1.3. Interferogram of the mirror flat position taken by a Zygo interferometer.

The configuration was chosen to obtain a deformation of the membrane on the edge of the active area thanks to the faced electrodes of the outer ring. Applying voltages to the upper electrodes the membrane moves towards the incoming beam and towards the back of the device. The possibility of push and pull the membrane allows to use the deformable mirror without biasing the membrane\(^2,3\) and to obtain better performances in terms of spatial resolution, Zernike polynomials amplitude and compensation of eye aberrations. These items will be analyzed in details in the next sections. The results will be compared with those obtained by the pull membrane mirrors realized in our laboratory and described in detail elsewhere\(^8\). The pull mirror uses a 18mm diameter membrane that has the optimal active area of about 10mm\(^8,9\). The typical rms deviation from a flat surface is less than 60nm. The maximum stroke obtained pulling all the electrodes at the maximum voltage of 230 V, is 3.5 \(\mu\)m in the active region of 10mm.

1.2.2 Push Pull mirror design

We developed a mathematical model for the prediction of the mirror deformation based on the analytical solution of the Poisson equation proposed by Clafin\(^9\). The model gives the possibility of design the mirror geometry and to optimize the generation of the first four radial orders of the Zernike polynomials. The evaluation of the reproduction is computed by the peak-to-valley amplitude and a term that we define Purity. Literature reports the ability in Zernike generation in terms of rms residual of the actual shape with the desired one\(^2\). We propose to quantify the mirror performances computing the Purity:
where the terms $D_i$ are the projection of the normalized shape $M(x,y)$ over the Zernike orthonormal base versor $z_i$:

$$D_i = \langle M(x,y) \cdot \hat{z}_i(x,y) \rangle$$

It is clear that $D_i=1$ if the $M(x,y)$ is parallel to $\hat{z}_i$, that it means that they have the same shape and $M(x,y)$ has no contribution from other non desired Zernike terms. Hence, the quantity $P_i$ represents how the generated shape is similar to the desired shape $Z_i$ and gives a measure of the contribution of different Zernike polynomials. We chose to use this representation because respect to the RMS residual, is independent from the peak-to-valley value, giving a more direct interpretation of the quality of the reconstruction.

The design of the mirror was carried out to obtain the maximum peak-to-valley values for the first three orders of the Zernike polynomials at the maximum values of Purity. Fig 1.3 reports the peak-to-valley values and the correspondent Purity as functions of the membrane normalised radius. The simulation has been performed using 37 lower electrodes and 9 upper electrodes faced to outer ring of the lower ones and the ITO coated glass disc.

The mirror optimal Active Region was obtained defining the Influence functions matrix as:

$$A = A_1 \ldots A_{47}$$

where $A_i$ are columns containing the influence functions relative to the $i$-th electrodes.

The vector of the electrostatic pressure $p$ is obtained, under the hypothesis of linearity, as:

$$p = A^{-1}Z(x,y)$$

where $Z(x,y)$ is the vector containing the desired shape.
The calculation of $A^{-1}$ was carried out using the non-negative constraints least square (NNLS, Lawson and Hanson algorithm)\(^9\) of the electrostatic pressures. The maximum peak-to-valley value is obtained for a normalised radius of 0.4, suggesting that for a membrane of 25 mm the optimal active region is 10 mm that corresponds to the whole area covered by the ITO glass. The minima in the peak-to-valley values correspond to the area closes to the places where the first derivative of the influence functions relatives to the actuators of the second rings are nulls (about in the centers of the electrodes). The maxima are placed about where the derivatives have their maxima which happens close to the separation between the second and the third rings. This configuration allows an optimum Zernike’s reproduction for normalised radius in the 0.3 to 0.7 range.

![Fig. 1.4. a) peak-to-valley amplitude obtained by the NNLS fitting of the first three terms of Zernike polynomials over the active region. The horizontal red lines represent the pad positions of the first, second and third ring. b) Purity of the first three terms of the Zernike polynomials over the active region.](image)

1.2.3 New algorithm for Zernike Polynomial Generation

In order to generate the desired shapes in open loop, the influence functions were measured. We used a Twyman-Green interferometer (Zygo) to measure the deformation caused by a single actuator which is called influence function $A_j$. Fig.1.4 shows some measurements of the influence functions. The maximum
displacement for the lower actuators is 0.8μm peak-to-valley relative to the active area. This low value is due to the excessive thickness of the spacer. By using a thinner spacer, the quality of the results can be further increased. The positive displacement due to the transparent electrode is easily recognizable in the upper actuators influence functions, with a 2.5μm peak-to-valley value. The external ring of upper actuators gives a maximum peak-to-valley displacement of 1.3μm and a minimum of 0.8μm. This asymmetry, clearly visible in the number of fringes in the interferograms, is due to imperfections in the realization of the calibrated frame. The maximum voltage applied to all the upper actuators (230V) gives a displacement of about 3μm. Since the edge of the membrane is covered by the electrodes, it was not possible to measure the value of the pedestal of each influence function. The results here presented are obtained using the pedestal values from the simulations.

Fig. 1.5. Examples of measured influence functions. Surface and interferograms are shown for the electrodes 2, 8, 20, 38, 42.
1.2.4 Performances

Literature reports several publications that relates the capabilities of deformable mirrors in visual optics, with the generation of Zernike polynomials. As suggested by Dalimier and Dainty\(^4\), this analysis is not completed because, as the Zernike terms are orthogonal, problems of maximum mirror deflection and electrodes clipping can reduce the capability of generating aberrations. We address the evaluation of the performance of the push-pull mirror using both the Zernike polynomial fitting and the reproduction of the ocular wavefronts. The results are compared with a pull membrane mirror with an equal active region.

The tests here presented are the generation of the first four radial order aberrations and of 100 aberrations based on the statistics of well-corrected eyes\(^10\).

Several methods were published\(^2,3,11-13\) on the techniques for the generation of a desired shape of deformable mirrors. We follow the open loop approach\(^9\).

Literature reports iterative algorithms in closed loop for the optimization of the mirror controls; these methods give better results because they take into account the non-linearities in the mirror response\(^2\).

1.2.5 Zernike Polynomials

We evaluate the mirror performance using as target the first four radial order of the Zernike polynomials. In order to full exploit the mirror capabilities the values exceeding the maximum pressure (p\(_\text{max}\)) are clipped as described in the following paragraph.

At first we calculate the vector \(p\) using (4). Than, we define the vector \(p' = \{p_i \in p, p_i > p_{\text{max}}\}\) and we set \(p_i' = p_{\text{max}}\ \forall p_i' \in p'\). We also define the sub-matrix \(A'\) of \(A\) according to: \(A' = \{A_i | p_i > p_{\text{max}}\}\), the sub-set of elements \(p'' = \{p_i \in p, p_i \leq p_{\text{max}}\}\), and the matrix \(A'' = \{A_i | p_i \leq p_{\text{max}}\}\).

The vector \(p''\) can be computed as:

\[
p'' = A''^{-1} [Z(x, y) - A' p']
\]

So, the new vector of electrostatic pressure is \(p = p \cup p''\).
The algorithm has to be repeated until the vector \( p^\prime \) does not contain any saturated electrode.

This iterative strategy is applied to increase the peak-to-valley amplitude of the desired Zernike terms until the RMS residual is lower than 10\%, to finally obtain the voltage vector to be applied to the mirror. The interferograms of the results are shown in Fig. 5 and Tab. 1. The mirror response is better for the lower orders, as attested by the purity and the good peak-to-valley amplitude. The worst response is related to the spherical aberration and the polynomial of order (4,2). This lack of performance is explained by to the values of the pedestal of the influence functions, as discussed previously, that weights more in the higher order aberrations for their limited peak-to-valley amplitudes. The ratio between the measured RMS residual and the peak-to-valley does not exceed 18\% as for the case of the (4,0).

The peak-to-valley results of the simulation compared to the ones obtained in the measures are shown in Fig. 1.6(a). The results asset that the linear model is in good agreement with the measurements.

![Interferograms of the main aberrations measured with Zygo interferometer.](image)

As a comparison with the pull membrane mirrors, we report the measurements of the generation of the first four order aberrations with one of the pull mirrors described above. The same strategy for aberration generations and measurements was followed. In this case, the membrane is biased at half of its optical power.
Tab. 1.1. results of the aberrations produced with the Push-Pull mirror.

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Peak to Valley (μm)</th>
<th>RMS deviation (μm)</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt</td>
<td>1.6</td>
<td>0.14</td>
<td>0.93</td>
</tr>
<tr>
<td>Defocus</td>
<td>2.6</td>
<td>0.20</td>
<td>0.97</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>2.1</td>
<td>0.12</td>
<td>0.96</td>
</tr>
<tr>
<td>Coma</td>
<td>0.3</td>
<td>0.05</td>
<td>0.83</td>
</tr>
<tr>
<td>Trefoil</td>
<td>0.9</td>
<td>0.10</td>
<td>0.92</td>
</tr>
<tr>
<td>(4,0)</td>
<td>0.6</td>
<td>0.11</td>
<td>0.41</td>
</tr>
<tr>
<td>(4,2)</td>
<td>0.2</td>
<td>0.03</td>
<td>0.61</td>
</tr>
<tr>
<td>(4,4)</td>
<td>0.4</td>
<td>0.09</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Fig 1.6. a) histogram of the Peak to Valley measurements of the main Zernike Polynomials obtained from the model (green) and measured (red). b) comparison between the peak to valley measurements of the Pull mirror (red) and the Push-Pull mirror (green).

The Fig. 1.6(b) reports the performance obtained with the two different systems. It is clear that, in general, the strokes induced by the push-pull mirror are higher than the ones obtained with the pull mirror.
1.2.6 Simulation of performance in visual optics

We followed the approach suggested by Dalimier. We generated a random family of 100 aberrations following the statistics presented by Castejon-Mochon. The amplitude of the aberrations was computed as normal distributed random variables around their averages, with their variances. The aberrations rotations was treated as white noise within $[0, 2\pi]$.

The reproduction is carried out using the least square method explained in the previous section. In order to full exploit the dynamics of both mirrors according to the statistics reported by Castejon-Mochon, we apply a bias to the optical system relative to the push-pull mirror at the same amplitude of the average value of defocus. As usual, the pull mirror was used biasing the membrane to its half power.

The average RMS values of the family is about 1\,\mu m. The residual of the corrected wavefronts is 0.3\,\mu m for the pull mirror and 0.1\,\mu m for the push-pull one. We underline that the RMS residual for the pull mirror is in good agreement with the value obtained by Dalimier. The improvement given by the use of a push-pull mirror in the optical system is about a factor 3.

Fig. 1.7. Residual wavefront rms error after fitting with Pull mirror and Push-Pull mirror over a 10mm pupil.
1.2.7 Conclusions

We have designed and realized a push-pull membrane deformable mirror by adding some electrodes over the top side of the membrane. The performances for its application in visual optics are evaluated by the capability of generating Zernike polynomials and ocular wavefronts. The results are compared with a pull mirror with performances similar to commercial membrane mirrors. The results assert that a definitive improvement in the peak-to-valley amplitude and RMS residual are obtained.
1.3 Sensorless adaptive optics system for the compensation of primary aberrations

1.3.1 Introduction

Minimization of wavefront (w-f) aberrations is an obvious and fundamental goal in the design of whatsoever optical system. On this respect, a lot of work and literature has been produced in the past as well as in the present days, showing the great interest and importance of the subject. However, in the great majority of the cases until a few years ago not a lot of attention has been given to problems related to the minimization of (time-dependent) optical aberrations. This was mainly due to the fact that normal optical systems operate in a static or extremely slow varying environment, or in a situation in which the time variations could be considered negligible. In all these cases, (rigid) optical elements, that is optical elements whose opto-mechanical parameters as refractive index and shape are not time dependent, can be very practically used. When necessary, simple mechanisms can be adopted to change the relative position of one or more optical elements (as is the case of any camera objective), or slightly modify the shape and curvature of an optical element (as actually happens with deformable mirrors in astronomy active optics) to maintain the focus of the system.

However in the last years the interest has increased also in the realization of what we can call “dynamical” optical systems: in this case, the optical environment in which the system has to work not only varies rather quickly with time, but mainly it varies in an unknown way. For this class of optical systems, slow mechanisms changing the optical parameter in a pre-defined way are not really useful, and adaptive optics (AO) with a closed loop control system has to be implemented. The most noticeable application of closed loop correction by means of AO in dynamical systems is the acquisition of astronomical images through the use of

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2* Published on: G. Naletto, at al, No wavefront sensor adaptive optics system for compensation of primary aberrations by software analysis of a point source image Applied Optics
ground based telescopes. In this case, to remove the star twinkling due to the time dependent local variations of the atmospheric density in the air column above the telescope, the w-f of the observed object is acquired and analyzed by a suitable w-f sensor, as for instance a Shack-Hartmann device, by means of dedicated algorithms. Then the precise information about the w-f distortion is suitably passed to an AO, as a fast deformable mirror, that changes its shape to compensate this rapidly time dependent aberrations. Many other optical applications are now making use of AO systems: for example, AO has been used to enhance the performance of free space optical communication systems, and very important it is becoming for off-axis aberration correction in microscopy applications. In many cases, however, it is not really necessary to have fast and accurate systems as those used by astronomers, and simpler instruments can be realized. A typical case can be the application of the AO technology to instrumentation dedicated to ophthalmic investigation. It is obvious that an AO system for this type of application has rather different requirements with respect to an astronomical one. On one side it can be a simpler instrument because there is no “continuous” variation of the w-f, so it is necessary to adapt the optical system only when changing the patient. However, on another side, a substantial difference that makes these instruments rather complex is that they also have to provide a suitable illumination generating the w-f to be analyzed, since the object of interest is not a light source by itself. Ophthalmic instrumentation is not an isolated case, and many other applications can be found in which the characteristics of an optical system need to be varied from run to run, with several minutes-to-hours time variations: from industrial instrumentation in slowly varying environment, to lab experiments, to alignment of optoelectronics devices. In all these cases, there is not a real need to have a fast and continuous monitoring of the instrument optical performance, with all the related complexity. For this type of applications it could be more convenient to have a simpler AO system, able to monitor only the slow variations of the w-f aberrations. To this end, we realized in our laboratories an instrument in which the wavefront first order aberrations are estimated by a software code which analyzes the image produced by an adhoc point-like source.
As in a classical AO system, the information obtained by this software is then given as input to a deformable mirror (DM) that changes its shape to reduce the aberrations. The obvious advantage of this instrument with respect to a classical AO system, is that the w-f sensor is no longer necessary: this reduces the cost of the instrument, and avoids all the problems related to maintaining the performance of such a device once installed and aligned. However, it also has the well known limitation that by a simple image analysis it is not possible to obtain the entire and correct information about the aberrations present in the system. Actually, the instrument we have realized is not able to remove at once all the aberrations of the system, as an AO system with w-f sensor can do: this instrument has been conceived to make a gradual reduction of the aberrations, by means of an iterative process which follows a predefined hierarchy in removing the various type of aberrations. At variance with other algorithms, this is not based on a stochastic optimization procedure, as the genetic algorithms applied to the AO systems\textsuperscript{19, 34, 35} or the simulated annealing algorithm.\textsuperscript{28} Rather, the performed image analysis allows the system direct the correction of the system aberrations: this permits to strongly reduce the number of cycles, and consequently the time necessary to realize the system correction from minutes to a few seconds. More specifically, since the whole process requires less than a hundred iterations, working at a standard\textsuperscript{39} frames/s rate implies that the whole process can be completed in 3-4 seconds or less. In the aim of realizing such an system, a suitable software has been written and tested:\textsuperscript{36, 37} this software and the strategy adopted in correcting the aberrations are briefly described in Sect. 2. The optical setup adopted to test this instrument is described in Sect. 3: for these tests a prototype DM realized in our labs,\textsuperscript{38} having slightly less than 12mm useful diameter and a \(\approx10\mu\text{m}\) maximum possible deformation (at the mirror centre), has been used. This mirror is based on the deformation of a nitrocellulose aluminium coated membrane by means of local variations of the electrostatic pressure between the membrane itself and a pattern of electrodes underneath. Since with this DM the deformation of the membrane can be actuated only in one direction, the possible aberration corrections that can be performed are somehow limited and often not sufficient to fully correct the system.
To overcome this problem, in some cases the DM is set to half its maximum deflection as the start position: this introduces some defocus, that can be compensated by axially shifting a lens somewhere else in the optical path, but then the DM can be effectively moved in a push-pull way. However, for allowing a wider range of the DM deflection, we preferred to avoid this solution: it is obvious that this put some limitation of the tested system, however the obtained results described in Sect. 4 shows that the system has performed extremely well, at least within this limitation. Actually, we have very recently developed and tested in our labs a new push-pull nitrocellulose aluminium coated membrane DM: since the under-way characterization of this new DM and relative controller is giving extremely positive results, we are very confident that in the next few months we will have an AO system able to fully correct the first order optical aberrations with no need of a w-f sensor.

1.3.2 Software concepts and aberration correction strategy

The principle at the basis of the designed instrument is rather simple. It essentially consists in analyzing the image of a known point-like source passing through the optical system under test, and modifying the deformable mirror shape according to the image analysis to reduce the image aberrations (see Fig. 1.8). In the great majority of the cases, the point source image that has to be analyzed is not directly available and has to be somehow created. For instance, in the case of a fundus camera, that is a camera dedicated to the observation of the human retina, an illuminated pinhole can be projected on the retina itself through a dedicated optical path. The light that is back-diffused by the retinal fundus acts as a point source, and its w-f can be analyzed to estimate the aberrations present along the optical path from the retina to the detector. The aberration estimation is performed by a dedicated software, that analyzes a first image $\text{Img}^0$ produced by the point source with the deformable mirror in its rest condition, corresponding to a shape described by the Zernike coefficients $\{Z_0; Z_1; \ldots; Z_n\} = Z_0$. The image is analyzed, and the possible presence of aberrations is evaluated, together with the direction of change of $Z_0$, that is the vector of sign of the gradient $r(Z)$: in our case we restricted to
Then the coefficients corresponding to the detected aberrations are changed, and the new \( Z_1 \) vector is addressed to the DM electrodes voltage estimation routine to produce the mirror shape that best approximates the shape described by the estimated Zernike coefficients.

![Block diagram of the software iterative procedure to minimize the aberrations in the optical system.](image)

The modification introduced by the mirror deformation gives rise to a new image \( \text{Img}^1 \), and the procedure is then iterated obtaining the sequence of images \( \text{Img}^0; \text{Img}^1; \ldots \text{Img}^k \) in which \( \text{Img}^k \) tends to be aberration free. It is worth noting that in order to keep the dimensionality of the search space low, thus improving the convergence speed, the aberrations considered (spherical, coma, astigmatism and defocus) are modified separately. This requires the introduction of a hierarchy in the aberrations, so that those higher in the hierarchy can be estimated without knowledge of those lower in the hierarchy, and vice versa. This strategy allows to develop image metrics specific for each aberration with the unique requirement that the metric have to be as insensitive as possible only to aberrations lower in the hierarchy, since those higher in the hierarchy are assumed already compensated for. The described aberrations ranking and the iterative nature of the algorithm allows the progressive correction of all the aberrations, starting from those higher in the hierarchy and ending with the lowest: after the image \( \text{Img}^0 \), corresponding to the vector of Zernike coefficients \( Z_0 \) is acquired, the spherical aberration is corrected by iteratively modifying the Zernike coefficients \( Z_0 \) describing the shape of the DM, until no spherical is detected; then the algorithm detects and correct
coma, defocus and finally astigmatism. The latter, on the basis of the given inputs, estimates the array \( \{Z_0^0; Z_1^0; \ldots; Z_n^0\} \equiv V^0 \) of voltages to be applied to the \( m \) electrodes of the DM.\(^{40-44}\) It is worth noting that the just described closed loop method of correcting the aberrations of an optical system is very stable, at least with respect to possible misalignments of the deformable mirror or aging of the mirror membrane. This stability is originated in the adopted approach to the problem, where, differently from instruments using a w-f sensor, we are not going to measure the w-f aberrations. With less ambition, the goal of this method is only to minimize the size of a reference target image in the detector focal plane: by obtaining this, the image quality of the optical system is optimal as well. It is also interesting to observe that in theory, if this AO system is working in an optical instrument, it is no longer necessary to realize a perfect alignment of the instrument itself, because any misalignment would be compensated by the DM.

### 1.3.3 Experimental setup

To check the performance of the described software, a rather simple optical testbed has been mounted (see Fig. 1.9).

![Fig. 1.9. Schematics of the optical setup used in the tests of the AO system.](image-url)
In this testbed the 527.5 nm visible radiation emitted by an LED diode source (SOU) is condensed by a microscope objective lens (Lcond) on a 10μm pinhole (PH). The radiation emerging from the pinhole is collected by a zoom lens (Lcoll) acting as a collimator; from an analysis of the zoom parameters, we estimated an effective focal length of 29.4mm and an f/2.6 aperture. The collimated beam is then spatially limited by a diaphragm (DIA) at 11 mm diameter, passes through a beam splitter (BS) and impinges normally on the DM. After back reflection, the beam is 90° deviated by the BS, and then it is approximately three times reduced in diameter (bringing it from 11mm to 4mm) by an a-focal newtonian system (L1comp and L2 comp). The collimated “compressed” beam can then follow two different paths. In the first case it is collected by a focusing two-lens system Lfoc (effective focal length 47 mm) that makes the image of the pinhole on the detector (DET). The latter is the PL-A741 PixeLINK CMOS digital camera (pixel pitch of 6.7 μm) which transfers the data to a PC via a FireWire interface. The whole optical system makes a ≈ 4.5 magnification of the pinhole, so that the nominal (aberration free) pinhole image diameter is of the order of 45μm, corresponding to about 7 pixels. In the second case, the collimated beam is deviated by a flip mirror (Mflip) and directly sent to an OKO Technologies Hartmann w-f analyzer (WFA). The latter, whose entrance aperture is about 4 mm (and that was driving the beam reduction), has been used to measure the wavefront aberrations before and after the correction performed by the DM, allowing an accurate check of the DM performance. The WFA w-f measurements are expressed in wavelength units, that we have calibrated assuming the source wavelength λ=527.5 nm. With this system, varying the focal length of the zoom lens Lcoll and by tilting the L1 comp lens, it was possible to respectively introduce controlled amounts of both defocus and astigmatism on the nominal pinhole image. Then, analyzing the acquired image, and estimating the present aberrations, the voltages to be applied to the DM electrodes are calculated and the mirror is consequently deformed, closing the loop.
1.3.4 Results

In this section, some exemplifying results obtained using the apparatus described in section 1.3.3 are shown. Three cases have been considered to show the capability of this system to correct the wavefront aberrations: case A), in which defocus is the main aberration; case B), where the main aberrations are astigmatism and coma; case C) where both defocus and astigmatism are present in an almost comparable amount. In all these cases, the root mean squared (RMS) w-f aberration is of the order of 0.5 waves ($\lambda/2$): this value has been selected to stay within the range of the possible DM corrections, which are presently limited by the possible membrane deformation of the used prototype DM. For each considered case, two plots showing the w-f before and after the correction are given in Fig. 1.10. Moreover, to quantify the goodness of the introduced correction, Fig. 1.11 shows in a graphical way the Zernike coefficient values before (red points) and after (green points) the correction. In these figures also the w-f peak-to-valley (P-t-V) and RMS values are given. Finally, to quantify the improvement in the w-f quality, Table 1.1 numerically summarizes all the showed results (only the main aberrations are considered). Some considerations can be done on the obtained results. Case A) is dominated by a defocus aberration “positively” oriented (i.e. with a positive value of the defocus aberration coefficient), which is the versus in which the pulling action of the electrodes on the DM membrane is effective in reducing the aberration; no other significative aberration is present. Looking at the quasi optimal w-f shape after the DM action, it is evident the excellent aberration correction performed by the system. To quantify this performance, we can note that the P-t-V has decreased to 40% of its initial value (but, looking at the w-f plot, it is evident that the P-t-V value would be much lower if a local problem at the edge of the w-f would not be present), that the w-f RMS value is now $\lambda/10$ (@527.5 nm), and that the defocus coefficient has been reduced by almost 90% without considering the sign of the Zernike coefficient. This result shows that the system is very effective in identifying and correcting this aberration. Case B) has no defocus, but a significative “positive” astigmatism (mainly the $C[2;2]$ coefficient) coupled to coma ($C[3;1]$ coefficient). It is evident from the saddle w-f shape that to
optimally correct these aberrations the pull-only action of the mirror membrane is not sufficient; in this case a proper correction cannot be expected. In fact, the obtained results show that the system has actually performed some correction, at least within the limits of the possible membrane deformation, but not sufficient to have an optimal performance.

Fig. 1.10. Wavefront surfaces (obtained with the WFA) before and after the DM correction for the three considered cases. The blue dashed lines over plotted to the Z axis represent the total w-f excursion.
Table 1.1. Zernike coefficients before and after the aberration correction.

<table>
<thead>
<tr>
<th>Case</th>
<th></th>
<th>Value (waves)</th>
<th>Value (waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>before correction</td>
<td>after correction</td>
</tr>
<tr>
<td></td>
<td>P-r-V</td>
<td>2.04</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>RMS</td>
<td>0.45</td>
<td>0.11</td>
</tr>
<tr>
<td>Aberration</td>
<td>Zernike coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focus</td>
<td>$C[2, 0]$</td>
<td>0.87</td>
<td>−0.10</td>
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<tr>
<td>Astigmatism</td>
<td>$C[2, 2]$</td>
<td>−0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>$C[2, -2]$</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>Coma</td>
<td>$C[3, 1]$</td>
<td>−0.14</td>
<td>−0.02</td>
</tr>
<tr>
<td>Coma</td>
<td>$C[3, -1]$</td>
<td>−0.06</td>
<td>−0.16</td>
</tr>
<tr>
<td>Spherical aberration</td>
<td>$C[4, 0]$</td>
<td>−0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Case B</td>
<td>P-r-V</td>
<td>3.20</td>
<td>2.45</td>
</tr>
<tr>
<td>RMS</td>
<td>0.45</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
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<td>Zernike coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focus</td>
<td>$C[2, 0]$</td>
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<td>−0.02</td>
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<td>0.34</td>
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<td>Coma</td>
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<td>−0.49</td>
</tr>
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<td>0.09</td>
</tr>
<tr>
<td>Spherical aberration</td>
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<td>−0.13</td>
<td>−0.13</td>
</tr>
<tr>
<td>Case C</td>
<td>P-r-V</td>
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<td>0.88</td>
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<tr>
<td>RMS</td>
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<td>0.17</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Focus</td>
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<td>−1.03</td>
<td>0.13</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>$C[2, 2]$</td>
<td>−0.03</td>
<td>−0.01</td>
</tr>
<tr>
<td>Astigmatism</td>
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<td>−1.15</td>
<td>−0.41</td>
</tr>
<tr>
<td>Coma</td>
<td>$C[3, 1]$</td>
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<td>−0.03</td>
</tr>
<tr>
<td>Coma</td>
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<td>0.04</td>
</tr>
<tr>
<td>Spherical aberration</td>
<td>$C[4, 0]$</td>
<td>−0.20</td>
<td>−0.08</td>
</tr>
</tbody>
</table>
Fig. 1.11. Zernike coefficient values before and after the correction for the three considered cases. Red points represent the aberrations before the correction, while the green ones are representative of the corrected w-f. In addition, the surface P-t-V and RMS values are reported.
In particular, the P-t-V has been reduced by about 25%, the astigmatism $y$ coefficient has been halved, and the RMS w-f value has been decreased to 0.3 waves ($\lambda/3$ @527.5 nm); all the other optical coefficients have not been varied in a significant way. Again, this is not an optimal result, but the actual limit is due to the present DM design, not to the implemented method: with a push-pull DM, the result would definitely be much better. Finally, case C) shows a peculiar and rather interesting behavior. In this case, the w-f has strong defocus and astigmatism ($C[2;2]$ coefficient), while all the other primary aberrations are much smaller. Since defocus has negative coefficient, owing to the DM pull-only limitation one could expect that the system is not able to correct it. However, in this case, the w-f does not have a marked saddle shape as in the previous case, and some corrective action can be done by the DM (looking at the w-f shape in Fig. 1.10, we may think that the DM is able to “pull up” the “lower” sides of the w-f). In effect, the obtained final w-f shows that the algorithm for the analysis of the pinhole image has been able to minimize the aberrations. The result is a considerable reduction to 25% of the P-t-V and a w-f RMS reduction to $\lambda/6$ (@527.5 nm), with a great decrease of all the aberration coefficients (see Table 1.1). Three other general considerations can be done. The first is that looking in Fig. 1.10 at the w-f's before and after the DM correction, it is clear that the DM is acting very well within its physical limitations. This makes us very confident that with the new push-pull DM, whose deformation range is also larger, a definitely much better aberration correction can be done. The second is that in all the presented cases the Zernike coefficients not involved in the correction process have not been sensitively modified. This permits to state that the introduced correction is obtained without degradation or perturbation of the not controlled Zernike coefficients, so confirming the goodness of the implemented algorithm for the aberration estimation by a pinhole image analysis. The final consideration is relative to the speed of the system. In all the tested cases, the algorithm takes less than 100 cycles to reach the “optimal” condition; since one cycle takes approximately $1/20 - 1/25$ s, the whole optimization takes just 4-5 s. However, presently we are not using a low noise camera, and some time consuming image filtering is necessary (mainly
at the beginning of the operation, when the image broadening is of the order of 20-30 pixels and the signal-to-noise ratio is very poor) to remove undesired features from the image. With a better camera, and perhaps some software optimization, we are confident that the time to realize the whole process can still be reduced.

1.3.5 Conclusions

The description of an adaptive optics system with no wavefront sensor to correct primary aberrations has been given. The system is based on an iterative process that analyzes a point source target image, gets some information on the present aberrations and consequently changes the shape of a DM to minimize them. The system has been tested with a prototype pull-only nitrocellulose aluminum coated membrane DM, and the obtained results show that the system works very well, reaching an optimal focusing condition in just a few seconds. The system is presently limited by the DM design, whose membrane deformation does not allow the correction of some aberrations. However, with a new push-pull DM recently developed in our laboratories we are confident to obtain a much better system performance. Such a system can be conveniently applied in all the fields in which a not real time optical adaptation can be accepted, and we are planning to use it on a new model of adaptive optics fundus camera presently under test.
1.4 References

8. S. Bonora, I. Capraro, L. Poletto, M. Romanin, C. Trestino and P. Villoresi, “Wavefront active control by a DSP-Driven deformable membrane mirror”, to be published on Review of scientific instruments (Accepted 24th July 2006)


Chapter 2. High speed control for free space communication
2.1 Introduction

This chapter regards the development of an electronic dedicated system for driving the deformable mirror. The improvement carried out is significant since usually the DMs systems are drive with PCI cards and a Personal Computer. The advantage is usually the easiness in writing codes (Matlab or Labview) but the system is pretty slow (about 10Hz). For application demanding high speed control such as atmospheric turbulence correction, a dedicated electronic is mandatory. The architecture we present here is based on a Digital Signal Processing microprocessor. The second section of the chapter is dedicated to the application of this system to free space communication. The set up with the communication enclosed is under test in these weeks.

2.2 High Speed mirror driving unit for membrane mirrors

2.2.1 Introduction

The most significant devices which are available to actively correct the wave front of a light beam include the liquid crystal modulators, the microelectromechanical systems MEMS, and the piezoelectric, as for the bimorph case, and the deformable mirrors. The liquid crystal modulators have the possibility of being used in transmission as adaptive lenses; furthermore they have relatively large apertures and high resolution actuators. The main drawbacks of these devices are the transmission losses, the scattered light due to their discrete structure, the chromatic behavior, and the limited amount of maximum optical power. These devices are successfully used in astronomy for the correction of the atmospheric turbulence and, driven by genetic algorithm, as phase modulators for ultrafast lasers with spectrally dispersed beams. Thanks to their high resolution, this configuration

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* S. Bonora et al, Fast wavefront active control by a simple DSP-Driven deformable mirror Review of Scientific Instruments 2006, September, 77
gives good results but with low efficiency. The MEMS devices are used in adaptive optics for their high resolution elements, small size, and low prices. These devices are present as segmented elements and also as membrane mirrors. They operate at high frequency, largely exceeding the kilohertz region. Their main limitations are the low reflectivity about 80%, the low power level at they can be exposed, and the limited maximum stroke in the micrometer range. The most successful fields of operation are opthalmology and the correction of beam wandering. Besides these devices, the deformable mirrors are divided into two main categories: piezoelectric and membrane mirrors. The former one have larger stroke and can operate with kilowatt laser because they can be actively cooled. Their limitations are the hysteresis and the high cost. The latter are cheaper and with low power consumption. We propose a device using these kinds of mirrors because of their important properties: they are lossless, they do not suffer chromatism, under appropriate coating they can be used with high intensity and ultrafast pulses, the good generation of the main aberrations, and large dynamics. The maximum stroke they can reach is relatively large as about 9–10 μm. Because of these properties, they have a widespread diffusion in a large class of applications: in visual optics for the correction of the diagnostic of the eyes, in astronomy for the correction of the atmospheric turbulence, in imaging optics for the improvement of the visual systems, and in the beam shaping of laser beams. In scientific experiments, exploiting the achromaticity and high laser load, they are used successful for the optimization of nonlinear processes. In these cases a suitable strategy to find the correct mirror shape is the genetic algorithm. In those experiments, the convergence time was in the order of few minutes because of some limitation in the hardware and software speeds.

2.2.2 Experimental setup

The aims of the work are to realize a system for either rapid correction of atmospheric turbulence in optical free space communication systems and for the optimization of nonlinear optical processes as high order laser harmonics generation. The mirror, I developed in our laboratory, is a thin nitrocellulose
membrane aluminum coated deformable by 37 electrodes as depicted in Fig. 2.1. It is deformed by electrostatic force created by applying a high voltage drop between the electrodes. The membrane is 5μm thick; its initial flatness is less than 60 nm rms. Pulling all the electrodes at the maximum voltage of 230 V, the distance from the central point of the deflected surface to the plano is about 10μm as depicted in the interferogram (see Fig. 2.2b). This deformation is a paraboloidal that corresponds to a focal length of about 2m. Figure 2.2 shows the interferograms, taken by a Zygo interferometer, of the flat surface and of the mirror pulled by the half of maximum voltage (115 V).

![Cellulose membrane Al coated](image)

**Fig. 2.1: section view of a membrane mirror.**

The deformable mirrors work for correction of the aberration by either applying the phase conjugation principle\(^9\) or in closed loop using an optimization strategy.\(^7,10\) For the aberration compensation, the mirror is used with a wave front sensor such as Hartmann mask. We developed a mathematical model of the mirror in order to be able to generate any desired shape.\(^11\) The voltage vectors that generate the main aberrations were computed by solving the Poisson equation for tensioned membranes. The deformation, obtained from a single actuator, is called influence function and the matrix that collects them is the influence function matrix. Using the least squares method under the hypothesis of linearity, the surface that better approximates the main aberrations can be calculated.
Figure 2.3 shows the interferograms of three main aberrations (defocus, tilt, and astigmatism). A closed loop configuration has been realized in order to show the capabilities of the whole system. As an example of application, the coupling of the light into a pinhole is optimized. In the scheme depicted in Fig. 2.4, the HeNe laser source is expanded to 8 mm, and the beam is reflected on a steering mirror and on the deformable mirror. Finally, the beam is focused (f=1000 mm) toward the 75μm pinhole; a photodiode captures the light and gives a voltage signal that is proportional to the amount of light that passes through the pinhole. This signal is the merit function. The initial situation, saved by a charge-coupled device (CCD) camera, is a spot size about ten times bigger than the pinhole (1.5mm). The goal is to improve the amount of light that enters in the pinhole and remove the aberrations appositely introduced in the alignment.

2.2.3 PWM Mirror drive unit

The easier way to generate the mirror driving signals is by means of high voltage linear amplifiers. This kind of amplifiers is characterized by a low efficiency (less than 50%). Moreover, to decrease the power consumption, the slew rate within the amplifiers is limited. Thus, the rate of change of the output high voltage, for an input step change, is not so suitable. To get good and linear output drive capabilities and a bigger slew rate, our mirror drive unit uses the pulse width modulation (PWM) to produce the high voltage driving signals for the mirror electrodes. Each \textit{ith} output channel of the mirror drive unit is a cascade of a metal-oxide-semiconductor (MOS) half bridge followed by a low-pass filter. The control
input signal on $ith$ block is a low voltage PWM signal, generated by the discrete-time modulator. Detailed description of the electronic behavior of this system is described in the publication associated to this chapter.

![Optical scheme](image)

**Fig 2.4.** Optical scheme

### 2.2.4 DSP control software

The kernel of the whole system is a DSP TMS320 C5502 card which performs three main tasks. It acquires the input signal from the photodiode (using the ADS7822 A/D 12 bit converter), runs the algorithm, and produces the 64 PWM signals (only the first 37 signals are used to control the mirror drive unit).

More precisely, all the PWM signals are created into the DSP memory and driven out from the processor via the direct memory access (DMA) channel and the external memory interface (EMIF) peripheral pins as shown in Fig. 2.5. All the 64 PWM signals are stored in a 128 element memory table (called signal table) where all the elements are 64 bit wide. The $nth$ element represents the $nth$ time slot of the 64 signals. In every column of the table, one period of the channel PWM signal is stored, i.e., in the $mth$ column a
Fig. 2.5. 64 channel PWM signal generator block diagram.

period of the mth channel signal is stored. We choose to split the period of the PWM signal into 128 time slots to have a sufficient granularity of the duty cycle. To store and drive out 64 signals with a 32 bit CPU architecture, we choose to use a multiplexing addressing method. With the aid of two address lines (A3 and A4), we control two external latches that freeze the 32 bit EMIF data bus. Finally, with the DMA channel 0, programmed to work in a double-indexed modality, it is possible to drive correctly all the 64 outputs. All the PWM signals have the same frequency carrier FPWM which is a function of the EMIF working frequency FEMIF. All the 64 duty cycles are completely user programmable by means of an internal memory vector (called duty-cycle table) that contains their values. This duty-cycle parameter is coded with an 8 bit word whose value spans from 0 (i.e., 0% duty cycle) to 128 (i.e. 100% duty cycle). It is important to note that the DMA engine that feeds the EMIF with the 64 signal values should work continuously and should never be interrupted by any mechanism in order to guarantee the signal temporal continuity. In order to meet this requirement, we exploit the dual-port capability of the DSP internal random access memory (RAM). All the auxiliary data and the code reside in a memory block different from the ones used to store the signal table. Therefore, the DMA channel is never interrupted by the CPU memory accesses.
2.2.5 Optimization by genetic algorithm

The mirror surface moves on 37 electrostatic actuators and the optimization is carried out on a space of 37 parameters. While traditional search techniques use characteristics of the problem to determine the next sampling point (gradients, Hessian, linearity, and continuity), stochastic search techniques do not need such assumption. The next sampling point is determined on stochastic sampling rules. A suitable strategy is the so called genetic algorithm.\textsuperscript{10,12} This search method is found to obtain optimal solutions in a wide range of applications. It simulates the evolution in K iteration of a population $P=\{v_1, \ldots, v_H\}$ of individuals each representing a mirror configuration $v_h=\{v_j, j=1-37\}$. The value $v_j=0$–127, called chromosome, is a digital value associated to the voltage applied to the $j$th actuator. In order to exploit this solution, we set first the initial population $P_0$ of the initial generation $k=0$ choosing randomly the chromosomes of each individual. After the measurement of a suitable merit function for each individual, they are sorted and those with the higher rating are selected for the following generation and reproduce themselves according to some strategies, in order to complete the population $P_{1}$. This process is repeated until we reach the $K_{th}$ generation or an ending criteria is met. In our C++ language implementation, we used, as reproducing functions, uniform mutation and arithmetic crossover (Xover). The first simply modifies some chromosomes of an individual in the $(k-1)th$ iteration according to

$$v_j^k = \begin{cases} v_j^{k-1}, & j \in A \\ \eta, & j \notin A \end{cases}$$

where A is a random subset of $\{1,2, \ldots, 37\}$ and $\eta$ is a random integer number $\eta<127$. The second combines two individuals of the $(k-1)th$ iteration as follows:

$$v_a^k = rv_a^{k-1} + (r-1)v_b^{k-1}$$

$$v_b^k = (r-1)v_a^{k-1} + rv_b^{k-1}$$

where $0<a$, $b<H$ are simply the indices of two different individuals and $0<r<1$ is a random number. Moreover, the implementation takes into account the memory usage in the DSP and is based on a fixed size data structure modified at each
iteration by pointers and also exploits the electric thermal noise to obtain truly random numbers.

2.2.6 Performances

A. Dynamic behavior

The dynamic behavior is characterized by measuring the frequency band of the mirror. We have tested the mirror in tilt deformation because of its interest in applications, such as atmospheric turbulence correction, quantum free space communication,\textsuperscript{13} and astronomy. The experimental setup is shown in Fig. 2.6. The band measurement was obtained unconnecting the feedback apparatus and using the adaptive mirror in open loop.

![Figure 2.6: Experimental setup for the mirror dynamic measurements](image)

We have applied two different voltage vectors that carry out two tilt deformations (see Fig. 2.3) opposite of 180° in order to exploit the maximum capabilities of the mirror. The amplitude of the deflection of the focal spot on the CCD camera is the measurement of the mirror dynamics. A switching frequency between the two positions in the 10–800 Hz interval was applied. The displacements were measured by a CCD camera with the asynchronous sampling technique. The results are shown in Fig. 2.8. The cutoff frequency at 90% is about 600 Hz which meets the requirement in high frequency applications and is comparable to other electrostatic deformable mirrors.\textsuperscript{14}
B. Closed loop experiments

A closed loop experiment has been ran to evaluate the capabilities of the genetic algorithm and the maximum speed of convergence of the system. The frequency of operation was set at 330 Hz. Depending on the focalization lens misalignment and the desired level of correction, we found that the number of generations needed for the optimization varies from 20 to 40. As we can see in Fig. 2.8, the central peak of the final spot is 120μm wide that is close to the diffraction limit for a beam of 8 mm in diameter focalized with a 100 cm. This attests the good result obtained in the optimization. The numbers of operations depends on the number of elements in the population. To solve this simple experiment, we have chosen a population of 50 elements. The average time needed for the optimization is 2.7 s for 20 generations and 6 s for 50 generations. As example, Fig. 2.9 reports a typical evolution of the voltage gained from the best elements reached at each generation. Important further information can be extracted from the observation of the correction evolution. To evaluate the speed of the convergence, the decomposition of the current surface in terms of Zernike polynomials was computed in several experiments. As an example, in the optimization of high-order harmonics generation of few-cycle laser pulses, the analysis suggests that the main aberrations are effectively corrected in the first 10–15 generations; after that, the optimization regards only higher order adjustments with effects on the fitness function.7

Figure 2.8: mirror band width
Additional data can be extracted using the mirror and a wave front sensor; complete phase front description can be used to understand the results.\textsuperscript{15}

![Image of spot before and after optimization](Image)

**Figure 2.8.:** spot before and after the optimization

![Image of voltage evolution](Image)

**Figure 2.9.** Typical voltage evolution on the photodiode over generations. The optimization was completed in 30 generations in 3.8 s.

**Discussion**

In conclusion developed a complete adaptive optics system for both closed loop optimization and high speed operation in real time beam position correction. The main features of these system are the speed of operation that can fully exploit the membrane dynamics, the low cost, and the compactness. The DSP technology allows the use as stand alone workbench station. The maximum speed of operation of the optimization using the genetic algorithm was 330 Hz atesting the
convergence time in few seconds. The correction of beam wander in long distance free space communication is discussed in the next section.

2.3 Deformable mirror in free space communication\(^4\)*

2.3.1 Introduction

Atmospheric turbulence is one of the most relevant limitations for free space optical communication. These are rapidly becoming very important either for classical last mile traffic distribution and for guarantee secure communication through quantum key distribution protocols (QKD) or chaotic steganography.\(^1,2\) Other attempts to solve this problem run at sub hertz loop frequency correcting only for slow drift due to daily temperature gradient.\(^3\) In urban environment the frequency of turbulence induced fluctuation is much higher and its correction requires different approaches such as fast adaptive optics devices. Electrostatic membrane mirrors are a relative inexpensive and better solution to this problem compared to MEMS or piezoelectric devices that present problems of low reflectivity, heat and costs.\(^4\)

2.3.2 Hardware and Software Description

The mirror, was completely developed in our laboratory according to the description of paragraph 2.1. In order to detect the tilt displacement at the focal plane of our receiver we use a PSD (Position Sensing Detector). This is a 9 x 9 mm Dumaa sensor with a resolution of 0.1\(\mu\)m, an analog bandwidth of 30KHz and a minimum input power of 1\(\mu\)W. Our mirror driver uses the PWM (PulseWidth Modulation) modulation to produce the high voltage driving signals for the mirror electrodes. The kernel of whole system is a DSP processor card that performs three

main tasks. It acquires the x,y analog signals coming from the PSD using a 12-bit AD converter and a multiplexer, runs the algorithm and produces the 37 PWM signals. The mirror, the electronics and the PSD sensor are depicted in Fig. 2.10 (left). The C++ software running in the DSP has been designed to facilitate calibration and usage in different operating conditions and to optimize the closed loop performances in terms of DSP memory usage and algorithm speed. The software also takes into account non perfect radial symmetry of the mirror itself compensating it in order to correct the maximum possible deviation.

2.3.3 3. Optical Setup

The optical setup for the characterization of the system is composed by the following elements. At the transmitter a 10mW, 850 nm laser diode and a red laser diode, used for initial alignment, are magnified by a keplerian telescope (M=12). At the receiver, 100m away from the transmitter, a Galilean telescope (M=0.13 ; D=8cm) collects the light that is subsequently directed toward the membrane mirror. After that the beam is focused with an f=150 mm lens and deviated towards a ND filter and an interferential filter before it reaches the PSD detector. A block scheme of the system is depicted in Fig. 2.10 (right).
2.3.4 Calibrations and Results

The overall tilt bandwidth of the system in closed loop configuration is found to be 400Hz with a max tilt of 400rad. The bandwidth is depicted in Fig. 2.9. In an acquisition of 60 seconds the rms displacement goes from 7.2μm (48μrad of tilt) to 1.4μm (9.3μrad of tilt) demonstrating an improvement of 5 times in the radius. A better picture of the situation can be deduced from Fig. 2.10, which corresponds to the trace of the centroid positions on the PSD detector screen after 60 second of integration, for the corrected and not corrected beam respectively. Notice that this image gives also a first rough measure of the correlation between the two axis that result almost uncorrelated. The corrected spot is comparable with the noise of the system measured during calibration in the lab. that is a limit for the displacement of the corrected beam. This corresponds of a rms tilt of 9μrad (rms displacement of 1.35μm). The maximum displacement caused by the turbulence (40μm) instead is not the maximum that we can correct i.e. the maximum tilt projected on the PSD plane (60μm for 400μrad). A frequency analysis has been carried out and the power spectral density is depicted in Fig. 2.11b.

![Image](image.png)

Fig. 2.11. a) Spot centroids trace on the PSD plane after an integration of 60 seconds. b) Power Spectral Density of the tilt induced displacement.

The correction system reduces unwanted tilt with a maximum frequency of 400 Hz. Although being present over the whole correcting bandwidth the effects of tilt correction at least in this setup and conditions is appreciable for frequencies up to 60Hz. Those result where used to calculate some useful parameter of the beam propagation: we have a standard deviation of 7.2μm on the position on the PSD due to atmospheric effects. Retracing the beam through the f = 15mm focusing lens and the M = 0.13 receiving telescope we calculate the tilt angle at the entrance of the receiver from the spot displacement on the PSD detector: we obtain
\[ \alpha_i^2 = 4.49 \times 10^{-11} \text{rad} \]

of tilt angle variance. Inverting the formulas for the tilt angle variance and the Fried coherence length for a horizontal path\(^5\) we obtain:

\[
r_0 = \left( \frac{a^2}{\lambda^2} \right)^{\frac{1}{3}} \frac{D^{\frac{1}{3}}}{1.83}
\]

\[
C_n^2 = \left( \frac{r_0}{1.68} \right)^{\frac{5}{3}} \frac{\lambda^2}{4L\pi^2}
\]

Plugging our results into these formulas we get a Fried coherence length of \(r_0=7.6\text{cm}\) and a index of refraction structure constant of \(C_n^2 = 3.16 \times 10^{-14} \text{m}^{-2/3}\). If we compare these values with a standard model such as SLC daytime Model\(^6\) we obtain: \(C_n^2 = 1.7 \times 10^{-14} \text{m}^{-2/3}\) and \(r_0=11\text{cm}\) demonstrating a good agreement with the experimental data.

### 2.3.5 Conclusions

The system presented is capable of correcting fast tilt jitter caused by atmospheric turbulence. It has been tested in an urban environment over a 100m optical path. All the devices and the electronics have been developed in our labs and are low cost and performing devices. The control software guarantees an easy set up and good correction capabilities with a reduction of the displacement variance up to five times. Further developments will be to test the system in increasing distances up to some kilometers, and integrate the system in a Quantum Key Distribution system in order to verify the increase in key rate due to the better spatial filtering.
References

Chapter 3. Ultrafast compression using deformable mirror
3.1 Design and realization of a membrane mirror for pulse compression

The ultrafast laser pulse compression is, usually, carried out by means of optical elements which act on the spectral dispersion in order to get a linear spectral phase and the shortest possible pulse duration.

The technology in this field is quite well developed and special configurations with positive and negative dispersion have been studied, realized and used (grating and prism compressors). Moreover mirrors with tailored spectral phase (chirped mirror) are available on the market for Ti:Sa lasers compression. Programmable devices are as well available on the market using different technologies (see Fig. 3.1):

- Liquid crystal Space Light Modulators (SLM)
- Acusto Optics Modulator (AOM)
- Deformable mirrors

All these three devices work very well for pulse compression and shaping. Each of them have advantages and drawbacks. For example SLM have a very high
resolution with some problem of pixellation (problem solved for the recently developed Liquid Crystal Light Valve) and threshold. They have been used successfully in a lot of experiments where pulse duration was more important that pulse energy. AOM is a very powerful technique, the resolution and damage threshold are quite high. Moreover, recent design using birefringent crystals, can be used without external dispersion elements such as prisms or gratings. Its limitation come from the maximum spectral range on which it can work. Both of these two elements can work efficiently in the near infrared but special design have to be drawn for being used in different spectral ranges such as Ultraviolet and Infrared. We carried out pulse compression at 1.6\(\mu\)m using a membrane deformable mirror especially designed. The main advantages of this technique is the low cost of the device, it can be used at any spectral range and that it doesn’t suffer of hysteresis.

3.1.1 Mirror design and realisation

We designed and realized a rectangular deformable mirror which can work for pulse compression in the 4f configuration as illustrated in Fig. 3.1. The design has followed the guidelines used for the realization of the circular mirror described in the previous chapters and in some publications of our research group.

The membrane is rectangular with a size of 47mm by 15mm. The interferogram of the membrane before mounting it id illustrated in Fig. 3.2.

![Interferogram of the membrane before being mounted.](image)

We decided to mount the membrane on a pads pattern as shown in the Fig. 3.3.
As first step of the mirror design we tried to identify the ideal length of the active region (region where the mirror is used for the correction) for minimizing the error in the shape reconstruction. This operation has been made iteratively on a active region mirror length ratio varying from 0.2 to 1. The result is illustrated in Fig. 3.4a, the minimum is obtained for a ration of 0.95. Fig. 3.4b illustrates the generation of a cubic function which correspond to correct a cubic spectral phase.

Another important issue is the reduction of the value of the transverse curvature on the mirror (section parallel the x axis on Fig. 3.3). Transverse curvature applies to the beam a transverse focusing which can be dangerous if it is comparable with the beam propagation length in the experiment. We underline that applying a constant pressure on the membrane, as the case of the electrodes shape illustrated in Fig. 3.3 the resultant deformation in the transverse section is paraboloidal.
In the attempt of making the mirror as flat as possible in a small part of the x axis centered around x=0, we tried to modulate the shape of the electrodes as illustrated in figure 3.5. Again playing iteratively on the parameters a2 and b2 we found their optimal values for a bidimensional active region of 45mm by 5mm. Figure 3.6 illustrates the inverse of the radius of curvature in that region for the quadratic and for the cubic function of the position y. The advantages obtained using the hollow electrodes are evident in the following figures with a reduction of the transverse radius up to half of the value relative to the full electrodes.

Fig. 3.5: shape of the electrode for increasing the transversal radius of curvature.

Fig. 3.6: inverse of the transverse radius of curvature for the parabolic and for the cubic function. Panel c shows a cross section for y=0 in the case of the full electrodes and of the shaped electrodes.
3.2 Sub-two-cycle light pulses at 1.6 μm from an optical parametric amplifier

3.2.1 Introduction

Light pulses with duration of just a few optical cycles are important for a number of applications, ranging from time-resolved optical spectroscopy to high field science. In the last decade such pulses have been generated by a variety of techniques: directly from a laser oscillator, by spectral broadening in a fused silica or in a hollow fiber or by an ultrabroadband optical parametric amplifier (OPA) OPAs seeded by a white-light continuum (WLC) not only provide broad frequency tunability but also enable to dramatically shorten the pulse duration because of their broad gain bandwidths. In fact the phase matching bandwidth Δω in an OPA depends on the group velocity mismatch (GVM) between signal and idler \( \delta_{si} = 1/v_{gs} - 1/v_{gi} \), where \( v_{gs} \) and \( v_{gi} \) are the group velocities of signal and idler respectively. To the first order one can write \( \Delta\omega \propto 1/|\delta_{si}| \), so that broadband gain is achieved when the group velocities of signal and idler are matched. This condition occurs either for type I phase matching around the degeneracy point (\( \omega_s = \omega_i \)) or in a non-collinear OPA (NOPA), in which the interaction angles are chosen to make the signal group velocity equal to the projection of the group velocity of the idler along the signal direction. The broad gain bandwidths of OPAs have been widely exploited for few-cycle pulse generation in the visible and around 800 nm, but so far the 1-2 μm wavelength region has not been explored and the shortest pulses generated in this spectral range have \( \approx 15 \) fs duration. Short pulses in this wavelength region are interesting for ultrafast spectroscopy as well as for high harmonic generation (HHG) and attosecond pulse synthesis, taking advantage of the extended energy cutoff afforded by the longer driving wavelength. We report on the generation of ultrabroadband near-IR pulses around 1.6 μm from an 800-nm-pumped OPA.

* Sottomesso a Optics letters: 11 Dicembre 2007
working at degeneracy and on their temporal compression by a pulse shaper employing a Deformable Mirror (DM). We produce pulses with μJ-level energy spanning the 1.2-2.1 μm wavelength range and compress them to a nearly transform-limited (TL) 8.5fs duration, corresponding to less than two optical cycles. These are to our knowledge the shortest light pulse generated at 1.6 μm.

Fig. 3.1. Broadband signal spectrum (solid line) detected with an InGaAs optical multichannel analyzer compared with the gain bandwidth calculated in undepleted pump approximation for θ = 20.61° (dash-dotted line) and θ = 20.73° (dashed line).

To show the Fig. 3.1 shows, as a dashed line, the frequency-dependent parametric gain, calculated in the plane wave approximation assuming monochromatic and undepleted 800-nm pump, for a 3-mm-thick β-Barium Borate (BBO) crystal cut for type I phase-matching. The broad gain bandwidth can be explained by recalling that, when signal and idler are group velocity matched at the degeneracy point, the Taylor expansion of the wave vector mismatch must be extended to the second order and involves the group velocity dispersion (GVD) of signal and idler beams. Such values are rather low in BBO, which has the zero GVD point at 1.45 μm, very close to the degeneracy point. It has been recently pointed out that in the nonlinear crystal bismuth triborate (BIBO) the zero GVD point is even closer to degeneracy (1.58 μm), allowing the amplification of still broader bandwidths. It should be finally noted that in Fig. 3.1 we have slightly
detuned the phase matching from the degeneracy point, allowing the obtainment of even broader gain bandwidths.

Fig. 3.2. (a) Experimental setup of the quasi-collinear near-IR OPA working at degeneracy; BS: beam splitter; VA: variable attenuator; HW: half-wave plate. (b) 4f configuration used for pulse compression with deformable mirror using an SF56 brewster-cut prism as dispersive element.

Fig 3.2(a) shows the experimental setup of the single-stage broadband near-IR OPA. The system is pumped by 80-µJ, 150-fs, 785-nm, 1-kHz pulses from a regeneratively amplified Ti:sapphire laser. A fraction of the pump with energy of approximately 2 µJ is focused in a 3-mm-thick sapphire plate to generate a single-filament WLC, used to seed the OPA; the remaining energy pumps the 3-mm-thick BBO crystal cut for type I phase-matching (θ=21°, φ=0°).

We use a very small angle (1°) between pump and seed to facilitate beam combination and separation and to prevent interference effects that would occur in a collinear configuration due to spectral overlap between equally polarized signal and idler. The amplified signal has an energy of 2±3 µJ and covers the 1200-2100 nm wavelength range (solid line in Fig. 3.1); the spectrum, acquired by an extended InGaAs Optical Multichannel Analyzer (OMA), shows, upon suitable adjustment of the phase matching angle, a two-peak shape in good agreement with
numerical simulations. The amplified pulses are sent to the DM compressor and characterized using Second Harmonic Generation Frequency Resolved Optical Gating (SHG-FROG)\(^{17}\). The OPA pulses support an 8.2-fs TL duration which corresponds to less than two cycles of the 1.6 \(\mu\)m carrier frequency (5.3 fs period).

Taking into account the linear propagation through the 3-mm-thick sapphire plate, the 3-mm-thick BBO crystal and the collimation lens, we can calculate that the zero group delay dispersion (GDD) point of the system is around 1.5 \(\mu\)m, with the blue wings of the spectrum experiencing positive GDD and the red wings negative GDD. The resulting spectral phase shows strong high-order dispersion contributions and, thus, is impossible to compensate using prisms- or gratings-based compressors. Only adaptive techniques can assure the accurate spectral phase control across the entire spectrum required to achieve optimum pulse compression.

Fig. 3.3. Upper panel: calculated deformation (solid line) obtained as best fitting of the desired one (dotted line) retrieved with FROG analysis; the green dashed line plots the wavelength dispersion on the mirror surface. Lower panel: voltages applied to each electrode in order to reach the wanted deformation.
In our compressor, shown in Fig. 3.2(b), the DM was placed in the Fourier plane of a 4\(f\) zero-dispersion pulse shaper consisting of a Brewster-cut SF56 prism and a spherical gold mirror (R=1000 mm). The DM is a 4-cm-long rectangular membrane electrostatic mirror activated by 30 linear electrodes (0-295 \(V\) range) which deform the silver-coated membrane, introducing a tailored optical path difference for each wavelength. We chose SF56 as prism material because it shows a good angular wavelength dispersion, enabling to fill the DM nearly completely, while adding a relatively low contribution to the pulse spectral phase. Furthermore, the use of a prism instead of a grating reduces the losses and the whole system, including two periscopes for polarization rotation, has a >70% throughput. A preliminary calibration of the mirror response was performed in order to define the influence function matrix which describes the effect of each electrode on the membrane shape. To this purpose, the mirror deformation obtained by applying a given voltage to each electrode individually was measured with a Twyman-Green interferometer. The mirror shape for optimum pulse compression was obtained by measuring the pulse spectral phase with SHG-FROG and introducing the additional phase required to correct it. The set of mirror actuator voltages required for the wanted deformation was computed by performing a pseudo inversion of the influence function matrix. Such process can be iteratively repeated acting on the residual phase after the previous correction (usually two or three times) in order to obtain a fine spectral control. The upper panel of Fig. 3.3 shows the required deformation, retrieved by the SHG-FROG measurement (red dots), and the obtained deformation (black solid line) calculated with the influence matrix. The voltages applied to the DM relative to that correction are presented in the lower panel. In such approach it is crucial to accurately map each wavelength-position on the mirror. The wavelength-position correspondence is nonlinear due to the peculiar prism dispersion. Therefore, before the compression procedure, we mapped the mirror by measuring with the OMA the wavelengths corresponding to 5 different positions and interpolating the results (green line in Fig. 3.3) with the angular dispersion function of the prism. This procedure also enabled to reproduce the compression results on a day to day basis,
without performing the above described retrieval procedure, by just performing the DM mapping and recalculating the voltages starting from the previously acquired phase. Figs. 3.4(a) and 3.4(b) show the experimental and retrieved 128×128 points SHG-FROG traces, measured with a 10-μm-thick BBO crystal, for the compressed OPA pulse, while Figs. 4(c) and 4(d) report the retrieved temporal and spectral intensity and phase profiles (rms retrieval error 1.8%). The measured 8.5 fs pulsewidth is very close to the TL duration, indicating that the DM based compressor allows dispersion compensation to all orders. Fig. 3.4(d) shows that the retrieved spectrum is in a good agreement with the directly measured one (Fig. 1) and that the residual spectral phase varies between ±1 rad, only slightly affecting the pulse duration.

FIG. 3.4. FROG measurement of the compressed near-IR pulses. (a) amplitude of measured FROG trace (128×128 pixels); (b) retrieved FROG trace in amplitude with 0.0107 reconstruction error; (c) intensity and phase profile as a function of time; (d) spectral intensity and phase.

3.2.2 Conclusions

In conclusion, we have generated sub-two-cycle near-IR pulses from a white-light seeded, 800-nm-pumped degenerate OPA with a deformable mirror compressor. We obtained μJ-level pulses covering the whole 1200-2000 nm spectral range with nearly TL 8.5 fs duration. The pulses produced by our simple
single-stage system are already suitable for time-resolved spectroscopy in the near-IR spectral range with an unprecedented resolution. In particular, the possibility of synchronizing them with the sub-10-fs visible pulses produced by a conventional visible NOPA\textsuperscript{21} enables a wealth of novel investigations on molecular systems. It should be straightforward to scale the output energy by 2±3 orders of magnitude, by adding one or two similar OPA stages\textsuperscript{12,14}, enabling the application of the energetic sub-two-cycle pulses to HHG. For such applications, it will also be possible to stabilize the Carrier-Envelope Phase (CEP) of the pulses by seeding the OPA with a CEP stable broadband pulse produced either by intrapulse difference frequency generation\textsuperscript{12,14,22} or by WLC generation with the idler of an OPA in which pump and signal are derived from the same source\textsuperscript{23}. 
3.3 References


Chapter 4. Bimorph mirrors for high power ultrafast lasers for $\lambda^3$

In collaboration with John Collier

Head of the Central Laser Facility (Rutherford Appleton Labs)

And Chris Hooker, section leader of Gemini
4.1 Introduction

This chapter is about the work I have done in my staying at the Central Laser Facility – Rutherford Appleton Laboratory in the United Kingdom. This research centre has a unique experience in designing and realizing lasers systems of very high power with short pulse duration. The ASTRA – GEMINI laser facility is a laser composed by three stages of amplification. At each stage corresponds a target area in order to carry out experiments. The last stage, called Gemini, began to fire in the beginning of October 2007 and represents the highest ultrafast energy laser of the world.6*

In this facility the use of adaptive optics for full exploitation of the laser capabilities began about ten years ago. Their studies have brought them to design and realize bimorph mirrors of large dimensions in order to match the ones for the lasers Vulcan and Astra. This cutting edge study has carried out an original design that has good performances using relatively low voltage driver. Their effort in developing adaptive optics technology is culminated with the realization of the largest aperture deformable mirror ever realized with bimorph design. I have taken part to their project realizing the 25cm mirror which is now a real outstanding device (section 4.2). The second issue I have taken part is the realization of an experimental setup for focusing an ultrafast beam with a fast optical element (section 4.3). This part of my effort has been orientated to develop a setup for making brand new science using the so called $\lambda^3$ regime. The interest for this regime is that at intensities higher than $10^{18}$ W/cm², the visible laser-matter interaction is governed by the electron relativistic behaviour entering in the domain of relativistic optics. This interaction results in a plethora of novel effects[1] X-ray generation, $\gamma$-ray generation, relativistic self-focusing, high-harmonic generation, electron and proton acceleration, neutron and positron production, as well as the manifestation of nonlinear QED effects. The work will carry on the next year using the setup in an experiment.

6* see: http://www.elf.rl.ac.uk/Facilities/AstraWeb/AstraGeminiHome.htm
4.2 25 cm bimorph mirror for petawatt laser

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory has been involved with the development of adaptive mirrors for more than ten years. During this time we have developed bimorph adaptive mirrors of 150mm diameter, and a control system operating at the few-Hz time scale for the correction of static and thermally induced aberrations in high-power laser chains. Such mirrors have played an important role in optimising the focusability of the petawatt beamline of the Vulcan laser. It would be highly advantageous to apply adaptive control to the full 220mm diameter of the Vulcan petawatt beam. As part of a LaserLab-funded European programme the Central Laser Facility (CLF) is developing large-aperture bimorph-type deformable mirrors, and have recently constructed a prototype mirror of 250mm diameter. The key feature of this mirror is that the piezoceramic plate is monolithic, rather than segmented. This prototype mirror is, to our knowledge, the largest deformable mirror so far realized with bimorph technology.

4.2.1 Manufacturing process

For a monolithic device, the size is determined by the maximum size of PZT disc that can be obtained, which is currently 220mm in the material we use. We have used a substrate of Pyrex of 250mm diameter and 5mm thickness. The completed mirror is able to handle laser beams of 180 mm diameter. The large-aperture mirror assemblies have been constructed, using UV-curing adhesive to attach the piezoceramic (PZT) disc to the substrate. The following stage has been to grind the PZT slab to the required thickness. To deposit the electrodes pattern on the back of the PZT slab we have used a photo resist mask. Spin-coating of photoresist is a well-developed technique that is widely used, and produces very uniform and

---

reproducible layers. The pattern is a scaled-up version of one used in previous adaptive mirrors, which has 61 actuators in total. Forty-nine of these control the shape of the mirror inside the beam footprint, and the twelve outer ones mainly contribute gradient control at the edge of the mirror. The resist also covers the outer part of the optic and the copper foil tabs that connect to the common silver electrode on the underside of the PZT.

![Fig.4.1. Left panel: back side of the mirror showing the pads and the wiring. Right panel: front side of the mirror.](image)

The sputtering has to be carried out in stages, as the sputtering sources generate a significant amount of heat. Once the resist had been washed away, the resistance between adjacent actuators was more than 20 MΩ. The next stage of the fabrication is to complete the polishing of the front face of the optic, and then to deposit a gold coating.

### 4.2.2 Mirror characterization

The mirror has been characterized as initial flatness, stroke capability, and dynamic behaviour. The initial flatness has been measured using a Zygo interferometer. The flatness of the mirror after the final polishing and coating was about 0.178rms (0.891μm peak to valley). After that the mirror has been glued in three points to the holder with silicon adhesive. The adhesive points and the weight of the mirror itself have created an astigmatic deformation of about 0.55μm rms (3.35μm peak to valley) as illustrated in Fig 4.2. Applying the same voltages to all the actuators a parabolic deformation has been added. We have investigated the maximum optical
power of the mirror ranging the voltage value from -64Volts to +64Volts. The maximum stroke has been estimated counting the number of fringes up to 30Volts (last interferogram with recognizable fringes) and interpolating linearly up to 64Volts. The peak to valley ranges from about -12µm to +12µm which corresponds to a radius of curvature of about 250m.

Fig. 4.2. Flatness of the mirror before it was glued to the mount. Interferograms of the flat position, applying +10V and applying +20V.

**Bandwidth**

In a second step we have measured the bandwidth of the mirror. The test has been carried out applying a sinusoidal voltage to all the actuators increasing gradually its frequency and checking the amplitude of the mirror movement. The mirror movement has been monitored by illuminating the mirror close to its edge with a collimated beam of small diameter. This beam has been cut to create a sharp edge that is projected on a wide area photodiode placed at about 2 meters distance. So if the beam cut is placed in the middle of the active area of the detector in the flat mirror position, each movement of the mirror determines a change in the illuminated area of the photodiode and so a different voltage. Following this technique we have obtained the results illustrated in Fig.4.3. Since our electronic driver has an operational limit of about 60Hz we have checked as well the rise time
of the mirror applying a voltage change from -50V to +50V. The results show that the rise time is about 1.2msec that correspond to a bandwidth of about 290Hz. Furthermore it is possible to observe that there is a ringing of the mirror position that has duration of about 10ms.

![Graph](image)

**Fig. 4.3. Bandwidth of the mirror movements.** Rise time with 10ms/div. Rise time with 1ms/div.

**Optical performances**

The optical performances of the mirror has been tested using an optical set-up composed by a green He:Ne laser beam a pin hole for generates a spherical wave front a collimation lens 15cm aperture and focal length of 140cm for generate a collimated beam, the deformable mirror and for focalization a lens of 75cm focal length and 15cm aperture. The sensor we have used is a Shearing Device Interferometer (SID4, Phasics). This device can measured wavefront of laser beams up to a numerical aperture of 0.16 so it is suitable for measuring the mirror deformation in our optical set up without adding any collimation optics. We have written a Labview program which, in closed loop, is able to measure the
deformation of each single electrode and to combine them in order to generate a desired mirror shape.

An example of electrode mirror deformation is illustrated in Figure 4.3 where the deformation caused by the central electrode and one electrode of the second ring are displayed. The peak to peak deformation imposed by the central electrode is about 0.6µm and 0.2µm for the second ring one (these measurements are relative to a circular section of the mirror of 15cm diameter). The software program automatically measure all the deformations generated by each electrode and store them in a matrix (mirror control matrix). The voltages v, which generate the desired shape, are calculated by the pseudoinversion of the mirror control matrix and its multiplication with the vector of the final shape:

\[ v = A^{-1} M \]

The pseudoinversion is carried out using the singular value decomposition in order to have the possibility of choose which mirror modes use for the control. The mirror is supposed to have a linear response.

![Hysteresys](Fig 4.4: Hysteresys of the mirror measured applying the same voltage to all the actuators and measuring the maximum displacement of the border from the center of the mirror. The hysteretic behavior of the mirror is illustrated in figure 4.4. The curve has been obtained applying the same voltage to all the actuators. A good rejection of the]
Hysteresis can be obtained applying a proper relaxation procedure before each measurement. In order to test the effectiveness of the correction the first trial has been the correction of the initial astigmatism of the mirror itself. As shown in figure 4.5 the initial deformation is 0.880µm pk-pk and after correction is 0.30µm with an rms value of about 11nm.

Fig 4.5: Interferograms of the initial deformation of the mirror, peak-peak 0.88µm, (the measure was taken on an area of 15cm diameter), and after its correction peak to peak 0.3µm and rms deviation from flat of about 11nm.

Some other trials to demonstrate the mirror ability in generating arbitrary shapes are depicted in figure 4.6 where an astigmatism and a coma shape have been chosen as targets.

Fig 4.6: Astigmatism and coma deformation obtained using the mirror in a circular portion of 15cm diameter. On the left side the aberration generated is astigmatism of 3.2µm pk-pk and in the right side coma of 1.8µm pk-pk.
4.3 Fast focusing

This section is dedicated to the realization of an experimental setup for the focusing of ultrafast laser beams using a F/0.5 off-axis parabola. The demonstration has been carried out using a green HeNe laser, and it is intended to be used in the Target Area 1 and Target Area 2 of the Astra laser. The final goal should be to have a laser intensity in the focus of $10^{18}$–$10^{22}$ W/cm$^2$. This intensity range has been recently reached by the group of G.Morou [1]. Experiments exploiting this setup are not reported in literature yet. The interests of this regime is that, for intensities higher than $10^{18}$ W/cm$^2$, we are in the relativistic regime which is still relatively unexplored from science. It is worth to notice that to reach the relativistic regime starting from a laser pulse of few millijoules and 50mm diameter with about 30fs duration we need to use an optical system with a focal length of 25mm, which means that the overall F/# is 0.5. It is known that this is an extreme optical system. Since we are using ultrafast laser beams we should notice that the only optical element we can use is reflective, since a refractive system would introduce temporal dispersion in the pulse.

So the only available optics for achieving this result is the use on an off axis parabolic mirror (OAP). The main task in using such a optics is the alignment, which is always critical with OAP, and its quality. Usually OAP are manufactured by diamond turning of copper bulks. Unfortunately, for this F/#, the manufacturer is not able to guarantee a quality good enough, so problems arising from slope errors. We should take care that with such a short F/# small deviation of the wavefront from the ideal flat have strong influence on the focal spot, and so on the intensity. So, in order to use this optical element, it is mandatory to use it in conjunction with an adaptive optics system to correct aberrations coming from the beam wavefront and from imperfection in the optical quality. The correction could be, in principle, carried out using an optimization algorithm for the correction of aberrations as was already done in the past [2,3]. It is not possible to use this method in our setup since the working speed of the DM is in the order of the seconds because of between a position and the following one a relaxation procedure must be carried out in order to suppress hysteresis.
It is interesting to not that at this regime the wavelength range of the beam is about 1μm, and as well, the beam spot is sub micron. This regime has been called by its pioneer Gerard Morou as *lambda cube*.

### 4.3.1 Mirror control

To perform the correction with the deformable mirror the methods we followed is the one described quickly in the previous section.

![Fig. 4.7: training setup with slow optical elements.](image)

The demonstrative setup is illustrated in the figure 4.7. The beam was expanded to 50mm diameter and collimated with a lens of 140cm focal length. A poor optical quality surface was inserted to introduce some arbitrary aberrations. The Deformable mirror was a bimorph, 150mm diameter, entirely developed at RAL for being used with the ASTRA laser. The focusing optics was a 1mt focal length lens. The wavefront sensor was Shearing Device Interferometer (SID4). It is interesting to notice that, since the SID4 has a numerical aperture of 0.16, for this setup it is not necessary to re-collimate the beam (as it would have been necessary with a Hartmann mask).

The technique followed was the one of the pseudoinversion using the Singular Value Decomposition (SVD). SVD is a factorization of a rectangular matrix with interesting applications. Given a matrix $M$ (m-by-n) over the field K, it can be factorized into:
\[ A = U \Sigma V^*, \]

where \( U \) is an \( m \)-by-\( m \) unitary matrix over \( K^m \), the matrix \( \Sigma \) is \( m \)-by-\( n \) with nonnegative numbers on the diagonal and zeros off the diagonal, and \( V^* \) denotes the conjugate transpose of \( V \), an \( n \)-by-\( n \) unitary matrix over \( K^n \). Such a factorization is called a singular-value decomposition of \( A \).

The SVD is interesting in our case since it is a method for obtaining an inversion of the matrix \( A \) and calculate the vector voltages necessary for driving the mirror.

**Pseudoinverse**

The singular value decomposition can be used for computing the pseudoinverse of a matrix. Indeed, the pseudoinverse of the matrix \( M \) with singular value decomposition \( M = U \Sigma V^* \) is:

\[ A^+ = V \Sigma^+ U^*, \]

where \( \Sigma^+ \) is the transpose of \( \Sigma \) with every nonzero entry replaced by its reciprocal. The pseudoinverse is one way to solve linear least squares problems.

**Geometric meaning**

Because \( U \) and \( V \) are unitary, we know that the columns \( u_1, \ldots, u_m \) of \( U \) yield an orthonormal basis of \( K^m \) and the columns \( v_1, \ldots, v_n \) of \( V \) yield an orthonormal basis of \( K^n \) (with respect to the standard scalar products on these spaces).

The linear transformation \( T:K^n \to K^m \) that takes a vector \( x \) to \( Ax \) has a particularly simple description with respect to these orthonormal bases: we have \( T(v_i) = \sigma_i u_i \), for \( i = 1, \ldots, \min(m,n) \), where \( \sigma_i \) is the \( i \)-th diagonal entry of \( \Sigma \), and \( T(v_i) = 0 \) for \( i > \min(m,n) \).

The geometric content of the SVD theorem can thus be summarized as follows: for every linear map \( T:K^n \to K^m \) one can find orthonormal bases of \( K^n \) and \( K^m \) such that \( T \) maps the \( i \)-th basis vector of \( K^n \) to a non-negative multiple of the \( i \)-th basis vector of \( K^m \), and sends the left-over basis vectors to zero. With respect to these bases, the map \( T \) is therefore represented by a diagonal matrix with non-negative real diagonal entries.
The application to our problem is that given the matrix $A$ of the influence functions collected as columns of $M$, the matrix $V$ represent an orthogonal base composed by the modes of the mirror. The values in the diagonal matrix $\Sigma$ are the gain of each mode. The gain values are in decreasing order, and the modes are ordered from the lowest spatial frequency to the highest. So the bigger gain corresponds to the lower spatial frequency mode. Figure 4.8 shows the modes of the mirror used in the experiment.

The fitting of the wavefront passes, at this step, through the determination of the ideal number of modes we need. Ideally the higher the number of modes the better the reconstruction. In practise we have two limitations. The first is that the voltages range is limited to ±64Volts and the second is the presence of noise. Using a high number of modes implies that we should be able to reproduce much better high spatial frequency modes. The main problem is that these modes have a small gain so, using a large amount of modes makes the algorithm saturates the voltages. Real aberrations cases are usually formed by low order aberration, the problem arise seriously because of the presence of noise. Measurements noise or artefacts get coupled with the highest orders driving the algorithm to wrong solutions and to saturation. Figure 4.9 shows the rms deviation of the generated wavefront from the ideal correction against the number of modes used. It is easy to note how the error is very low for a number of modes in the range of about 10 to 22. As it easy to imagine using few modes doesn’t give enough resolution for fitting the solution. As explained before for a high number of modes the noise plays a role that tend to reduce the system performance. The standard deviation of the voltages level against the number of modes used is illustrated in figure 4.10. Comparing the figures 4.9 and 4.10 it is easy to note that after about 20 modes the voltages level increases with a deterioration of the results.
Fig. 4.8: modes relative to a 15cm bimorph mirror

Fig 4.9: rms error in the fitting of the solution against the number of modes used.
4.4 Closed Loop

The setup for the fast focusing is illustrated in figure 4.11. The main components are: a laser beam (green HeNe) coming from a collimated pin-hole source, the deformable mirror, the AOP, a collimation optics and the SID4.
The OAP is 3” diameter with a focal length of 25 mm. Since we have used it with a beam of 50mm diameter, in order to train our system to correct beams similar to the one of Target Area 2, the numerical aperture of the optical system is about 0.6. The collimation optics is a microscope objective. The performance of the objective are conform to the use with broadband laser beams. Its properties are: long working distance, apoplanatic, apochromatic, infinite corrected over a wavelength range of 0.5μm to 1.5μm (Mytutoyo).

![Interferograms](image)

Fig. 4.12: Left panel: Interferograms of the wavefront before correction (pk-pk=2.00waves, rms=0.208waves). Right panel: Interferograms of the wavefront after correction (pk-pk=1.00waves, rms=0.026waves).

As it is easy to imagine the alignment of the system has been time consuming. The results of the correction applying the strategy illustrated in the previous section are illustrated in figure 4.12. The set of voltages relative to this solution are in Fig EEE. A detailed treatment of the propagation of laser beams through OAP is reported in reference [1].

The spot image has been obtained imaging the spot plane on a screen moving slightly the microscope objective by its collimation position. The images of the spot are illustrated in figure 4.13. The spot size has been obtained calibrating the
image using 10\(\mu\)m pin hole aligned to the focal plane of the OAP in order to be able to see the spot image through the pin hole. After this alignment stage, we have back illuminated the pin hole in order to have on the detector its image and be able of measuring the spot size.

![Spot Image](image.png)

Fig. 4.13: Measurement of the magnified image of the focal spot. Left panel: focal spot before correction. Right panel: focal spot after the correction (0.61\(\mu\)m FWHM).

The results is really good and in agreement with previous literature. The only interrogative point is relative to the aberrations introduces by the collimations optics which is again a critical elements since its very high numerical aperture. The advantage is that this optical element is refractive, so the alignment can be carried out using some references.
The technique used was to mount the microscope objective on a XYZ translator stage and on a tip tilt mount. Aligning carefully up to when, scanning along the optical axis, the beam keep staying on the axis itself should guarantee a good degree of alignment. Another test we planned to carry out was an aberration test such as for example a Foucault test or a Ronchi test. Unfortunately there was no time for doing these tests but they will be useful before performing a real experiment. Again with reference to the paper [1] they approach the validation of the methods using a simulation of the propagation of the beam through the optical system. The beam parameters has been taken by the intensity and hartmann phase of an image plane of the beam on the deformable mirror. From these data they have computed the focal intensity in the focal plane for both cases of the aberrated and corrected beam. From their comparison with a real image of the parabola focal plane they where able to state that the collimation optics was not introducing any important aberrations. I would like to say that this approach, although correct, is very critical especially in the case of the corrected beam. The Rayleigh range of that beam is about 1μm, so it is experimentally very difficult to perform a good enough image of the spot plane. I personally think that a Foucault test should give an easier and practical method for solving this problem.
4.5 References


I reported all the results and the progress we made in adaptive optics during the three years of my doctorate. We demonstrate that the application of adaptive optics is still a research field with interesting and important outcomes. I have been participating mostly in the device design, realization and testing of deformable mirror for: visual optics, single photon free space communication, pulse compression and fast focusing.

In all these applications I developed original solutions to the problems proposed. In each of the applications, which are described along the chapters of the thesis, I have collaborated with important teams.

About visual optics I took care of all the aspects of the design, realization and testing of the push pull membrane mirror which is the first prototype of this kind. The application of this mirror in visual optics is running in this days. This device gave me the possibility of establish a collaboration with Prof. Chris Dainty which is the director of one of the most important research group in Adaptive Optics such as the Applied Optics Group of Galway. Moreover I had the honor of being invited from him to give a seminar for his group about the push-pull mirror technology.

It is as well an important result the high speed driver for the compensation of atmospheric turbulence. This work put together three main different aspects: Digital Signal Processing electronics driver, deformable mirror technology, and
single photon free space communication. We had several people involved in this project. My role was the realization and testing of the DMs and the testing of the system.

Chapters 3 and 4 are about the realization of deformable mirrors for femtosecond lasers and science. In chapter 3 I designed, realized, tested and calibrated the DM for the compression of ultrafast pulses in the infrared. The results were impressive. We were able to generate the shortest pulse ever realized in the Near Infrared around 1.6μm. This result is important as well because we have used it in December 2008 for measuring for the first time the transition time of a photo excited Mott insulator transition purely electronic. The results of this experiment will be presented at the Ultrafast Phenomena 2008 and published soon.

In chapter 4 I have realized the largest DM with bimorph technology. This mirror will be used on the Vulcan laser.

We have several perspective for the future: development of push pull mirrors for pulse shaping, improvement of the push pull mirror technology, use of the fast focusing set up in a real experiment.