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Design and construction of a prototype of a flat top beam interferometer and initial tests.

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Abstract. A non-Gaussian, flat-top laser beam profile, also called Mesa Beam Profile, supported by non spherical mirrors known as Mexican Hat (MH) mirrors, has been proposed as a way to depress the mirror thermal noise and thus improve the sensitivity of future interferometric Gravitational Wave detectors, including Advanced LIGO [1]. Non-Gaussian beam configurations have never been tested before [2] hence the main motivation of this project is to demonstrate the feasibility of this new concept. A 7m rigid suspended Fabry-Perot (FP) cavity which can support a scaled version of a Mesa beam applicable to the LIGO interferometers has been developed. The FP cavity prototype is being designed to prove the feasibility of actual MH mirror profiles, determine whether a MH mirror cavity is capable of transforming an incoming Gaussian beam into a flat top beam profile, study the effects of unavoidable mirror imperfections on the resulting beam profile and gauge the difficulties associated with locking and maintaining the alignment of such an optical cavity. We present the design of the experimental apparatus and simulations comparing Gaussian and Mesa beams performed both with ideal and current (measured) mirror profiles. An overview of the technique used to manufacture this kind of mirror and initial results showing Mesa beam properties are presented.

1. Introduction

The Mesa beam profile has been proposed [1], [3] to mitigate the effects of thermal noise in Gravitational Wave Interferometer mirrors.

It is possible to generate a significant reduction in all sources of mirror thermal noise using modified optics that reshape the beam from a conventional Gaussian profile into a Mesa-beam shape. The interferometer's output phase shift is proportional to the difference of the test masses' average positions, with the average being performed over all points of a mirror test-mass face, weighted by the light's energy flux. If the intensity distribution is flat in most regions of the mirror, then the adjacent valleys and bumps created by thermal noise will average out. If, instead, the laser beam energy flux used to probe the test mass surface is rapidly changing, as is the case for a Gaussian beam, then the valleys and bumps will not average out equally well and the thermal noise will be enhanced. Wider light beam profiles then induce lower measured noise. These considerations suggest that large-radius, flat-top beams with steep edges will lead to smaller thermal noise than small-radius, peaked Gaussian beams with more gradually sloping sides (see figure 1).

A study of the gain factor broken down for test mass TN shows an improvement in sensitivity of about a factor of 1.8 if the mesa beam is used [4].The transition from LIGO's baseline design to non spherical mirrors does not significantly impact on the mechanical and topological design of the interferometer. The implementation of Mesa beams, to first approximation, requires only the replacement of the mirrors of the injection system, and an increasing in the precision of the mirror controls and alignment [5].

2. Design of the experimental apparatus

The test interferometer was designed to be a scaled down version of an Advanced LIGO arm cavity. The nominal parameters of Advanced LIGO [7] and the MH mirror construction constraints, which require a mirror of at least 2 cm, forced us to develop a single "half" cavity L'= 8 m long.

The length of available INVAR bars dictated the use of a folded cavity and fixed the cavity length at a 7.32 m. We designed a FP cavity with a MH end mirror at one end and a flat input mirror at the point that would be the waist of the LIGO interferometer. We built the folded cavity inside a rigid structure, using low thermal expansion coefficient materials (INVAR $\delta = 1.18 \cdot 10^{-6}$ /°K) for longitudinal stability and to prevent possible alignment instabilities due to differential thermal expansion of the materials in the interferometer. The cavity is suspended to avoid seismically induced vibrations exciting resonance in our interferometer and disturbing operations. The structure comprises 3 INVAR rods, 31.75 mm in diameter and 3657mm long, spaced at 120° on a 336.5 mm diameter circle stiffened by 5 spacer plates solidly clamping the rods at equal intervals. An aluminum thermal shield is used to minimize temperature variations.

The two end mirrors are mounted side by side on the first spacer plate while the folding mirror is located on the final plate at the opposite end of the cavity. The control of the mirrors is made by means of triplets of micrometric screws and piezoelectric actuators mounted at 120° at the periphery of each mirror.

The second and the fourth spacers are also used to suspend the cavity for seismic isolation. The entire structure is suspended by a system of four wires for horizontal isolation and GAS [8] blades for vertical isolation. The suspension system is formed by an arrangement of 4 couples of GAS designed to suspend 22 kg each. The suspension point can be finely adjusted using parasitic springs and stepping motors. The working point of the GAS blades was found using an iterative procedure [9] and has a typical frequency of 0.4 Hz. For optical stability and thermal isolation the entire system is enclosed in a custom vacuum tank. The structure of the FP cavity [10] is shown in figure 2.

3. MH mirror construction

The production of the MH mirror was performed at LMA Lyon [11]. The MH profile is obtained by differentially depositing SiO_2 glass with the desired radial profile over a flat substrate. The construction of a MH mirror (shown in figure 3) consists of 2 main steps :

Rough shape coating:

This process deposits a coating with the general shape of the MH to a precision of 60 nm. This is made interposing a static mask between the sputtering source and a rotating mirror substrate. The mask profile is calculated according to the desired mirror profile. The maximum thickness that can be deposited with this technique is of the order of a few thousand nm. Thin mirrors warp under the surface stresses caused by the deposition of coating materials. In our geometry, in order to maintain sufficiently tight surface tolerances, the thickness of the substrate must not be less than 0.4 times the diameter. We decided on a 50 mm diameter by 30 mm thick substrate, although the MH profile only extends over the central 20 mm, allowing space for the piezo actuators outside the optical profile of the mirror.

Corrective coating:

The rough coating is a dead reckoning technique, inadequate to attain the required mirror profile precision. To solve this problem the mirror profile achieved with the first deposition step is measured interferometrically and compared with the theoretical shape of the MH to generate a correction map. A small orifice mask is then placed between the source and the mirror producing a small pencil of sputtered atoms. The substrate is subsequently translated to paint atoms where the profile is too low. Adjusting the dwell time in each location controls the local correction thickness. This method corrects the coating thickness with a precision of less than 10 nm PV (Peak-to-Valley). With this technique is not practical to correct more than 100 nm of deviation because of the much lower deposition speed.

The main limitations of the corrective technique come from the measurement of the wave front, from the movement precision and from the size and sharpness of the SiO_2 corrective beam. The smaller the mirror is, the more difficult it is to get the necessary precision. It is difficult to generate the steep slopes required by small size mirrors. Indeed the minimum size of a constructible MH mirror (and consequently the minimum cavity length) was set by the maximum measurable slope (500 nm/mm) in the interferometric mapping step. The 20 mm diameter MH mirror used supports a 10 mm FWHM spot with 1 ppm diffraction losses. Additionally it should be noted that the measurement is less precise at the edges than in the central part and less precise corrections can be expected at the rim of small diameter mirrors. Building the larger diameter MH mirrors required by a full scale interferometer will be much easier.

4. Optical layout

The optical setup of the experiment can be divided in three parts: the input optics, the FP cavity and the profile readout optics.

The input optics of the experiment include the Nd:YAG Mephisto laser, a Faraday isolator, a system of lenses to match the input beam's waist and divergence to the cavity and a system of flat mirrors to align the laser beam through the input mirror.

The FP consists of 3 mirrors with power reflectivity of 0.95 for the flat input mirror and 0.999 for the flat folding and MH mirrors.

The profile readout optics were placed along one of the two transmitted beams from the folding mirror allowing study of the resonant transverse electromagnetic field at different distances from its waist without interfering with the input optics. The beam intensity profile is acquired by a Coherent Laser IIID CCD camera (240 x 240 pixels with a spatial resolution of 16.9 x 19 μm and accuracy of 3% per pixel). The transmitted beam from the end mirror is used to generate the feedback control signal to lock the cavity and to study how external noise affects cavity stability. The control signal is generated by a fast photodiode and then processed by a servo loop circuit capable of implementing both side and dither lock schemes.

5. Simulations

An implementation of a fast Fourier transform model [12] was used to simulate the behavior of our FP cavity with actual MH mirror maps.

The expected beam shape has been studied using an interferometric map of each mirror produced at LMA. Comparisons of the three test MH mirrors indicate to us which deviations we can expect from the ideal Mesa beam profile produced by a perfect mirror. Figure 4 (c) shows the deviation of one mirror from design specification: in particular, a significant slope respect to the outer rim (~ 1 μrad) on the central bump of the "Mexican hat" is present. This defect is present, to different degrees, in all of the sample mirrors. This tilt affects the resulting resonating fundamental mode (figure 4 (b)). Our simulations show that tilting the MH mirror by an appropriate angle can partially recover the Mesa beam shape (figure 4 (d)). It is also clear that small range mirror imperfections reduce the flatness of the beam profile, while the steep slope of the power distributions is well preserved.

The impact of misalignments and various degrees of mode matching of the input Gaussian beam on the resulting Mesa beam profile has also been carefully studied. The simulated beam profiles showed reasonable agreement with actual data [13].

6. Results and Conclusions

After the preliminary tests made with spherical mirrors to validate the mechanics and the optics of the experiment, we switched to a MH mirror.

Initial results with spherical mirrors showed a small but significant deviation from Gaussian beam profiles, perhaps due to imperfections and warping of the three mirrors. The cavity was then successfully locked with the MH mirror; very preliminary results are shown in figure 5. Higher order modes such TEM10 (figure 5 (c)), TEM11 and TEM20, in the cylindrical nodes denomination, have been clearly seen.

Attempts to improve the alignment have not resulted in satisfactory mesa beam profiles. A possible cause of this may be the warping of the two flat mirrors in the cavity, which may have also generated the deviations from Gaussian profiles observed in the preliminary tests. We have, so far, been unable to lock on a stable flat top beam. However we are able to lock the cavity on higher order transverse modes. The resulting higher order mode beam profiles show good agreement with theoretical predictions.Early tests indicate that our difficulties in tuning the interferometer to a centered TEM 00 mode may originate from deformations of the flat mirrors due to the three-point stress imposed by the mirror alignment piezos (significant deviations from the expected profile were observed even in the preliminary tests with the Gaussian beam profiles). We believe that the effect is predominant in the flat input and folding mirrors whose substrates are one third as thick as that of the MH. Work is in progress to improve the alignment and to modify the mirror holders to mitigate the deformations in the flat mirrors. After solving the flat mirror warping problem we will make measurements with the other two MH prototype mirrors and compare these results with simulations to determine the sensitivity of the beam profile to manufacturing mirror imperfections.

7. Figure

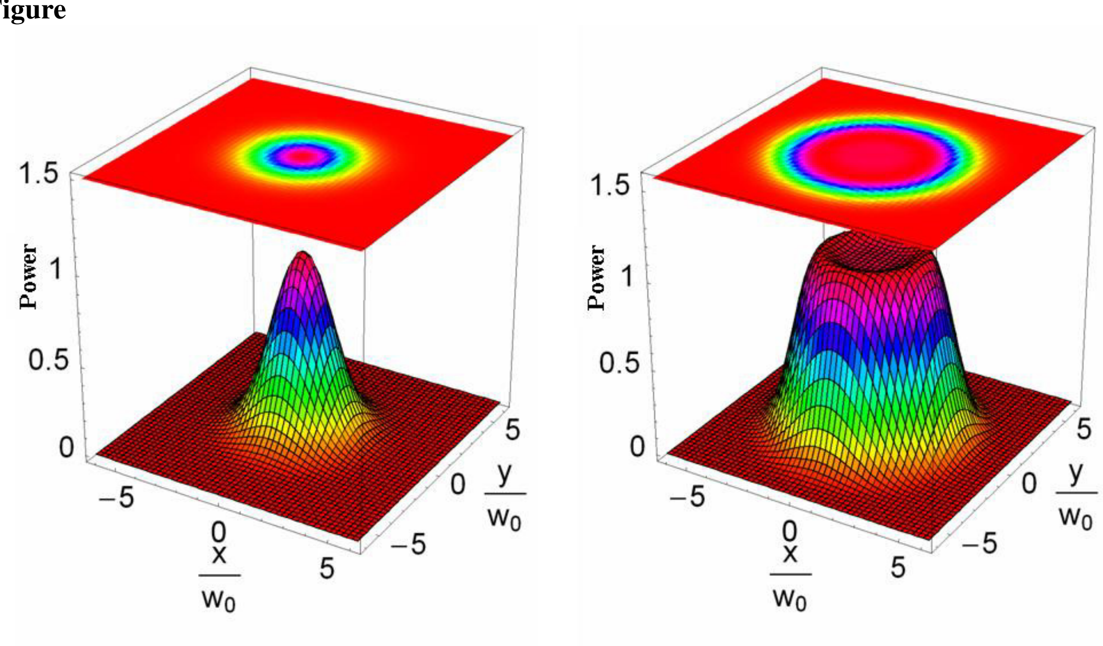

Figure 1 Comparison between Gaussian and Mesa beams [6] with the same diffraction losses.

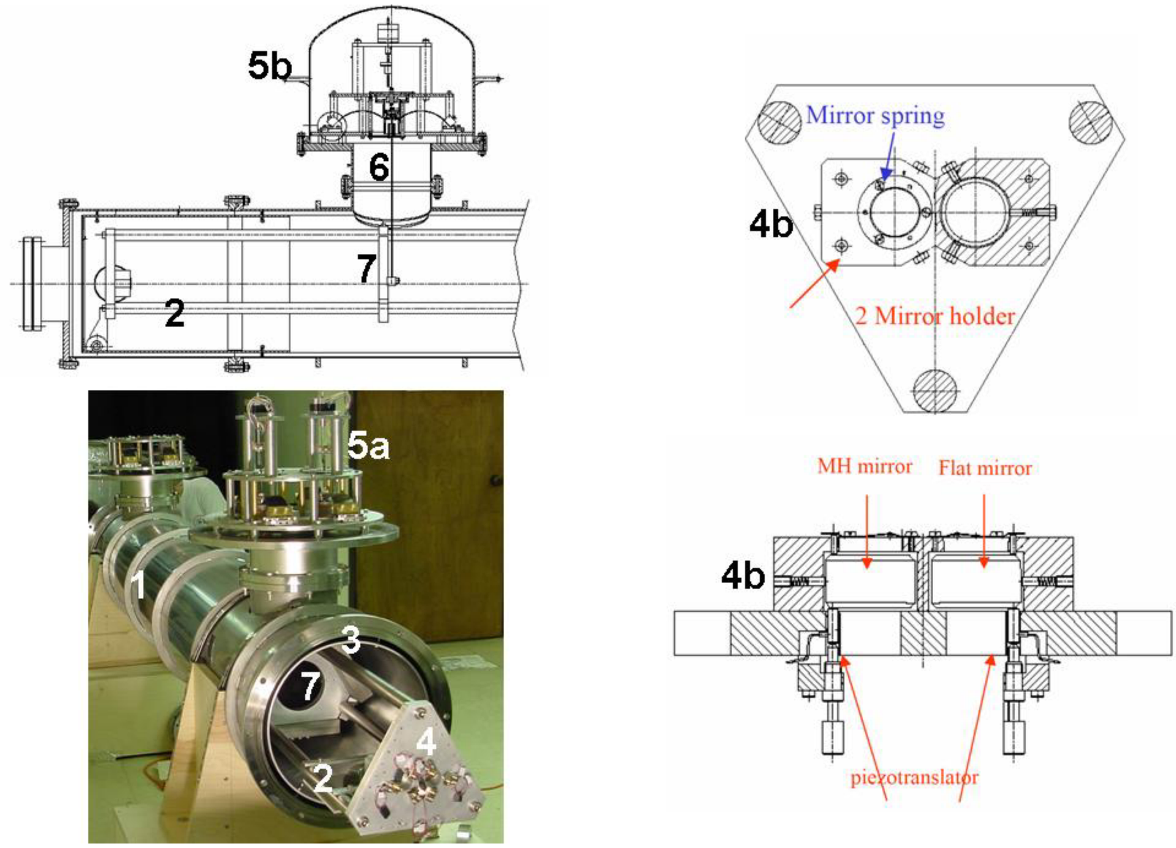

Figure 2 Experimental apparatus: 1 The vacuum tank that encloses the entire structure. 2 Invar rods. 3 Thermal shield. 4a, 4b Picture and technical drawing of end plate: showing: the piezoelectric actuators used to control the mirror position, the mirror holder and the mirror spring. 5a, 5b Picture and technical drawing of the suspending system. 6 Maraging wire.7.Spacer

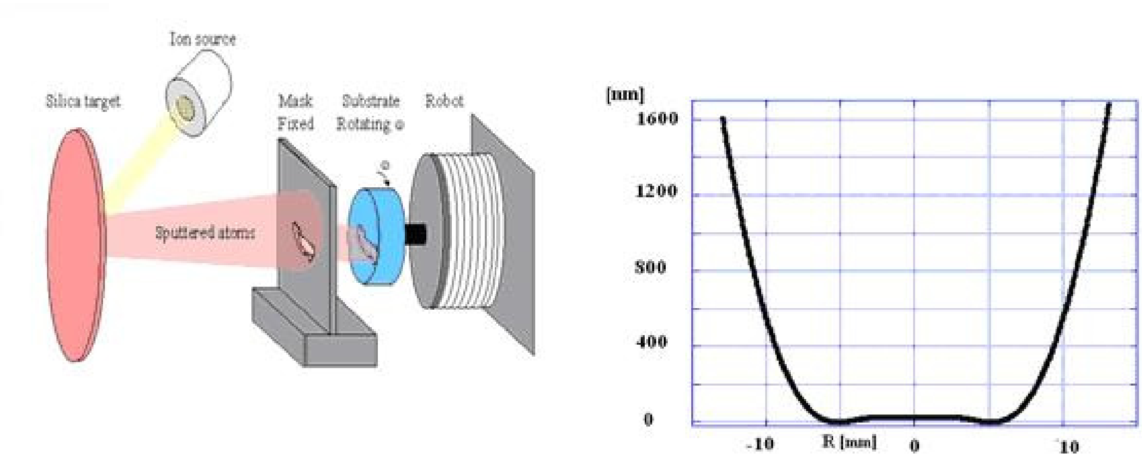

Figure 3 (a) Rough shape coating technique. Deposition of coating starting from a flat substrate, using a profiled mask between the ion source and the rotating substrate. (b) MH mirror profile.

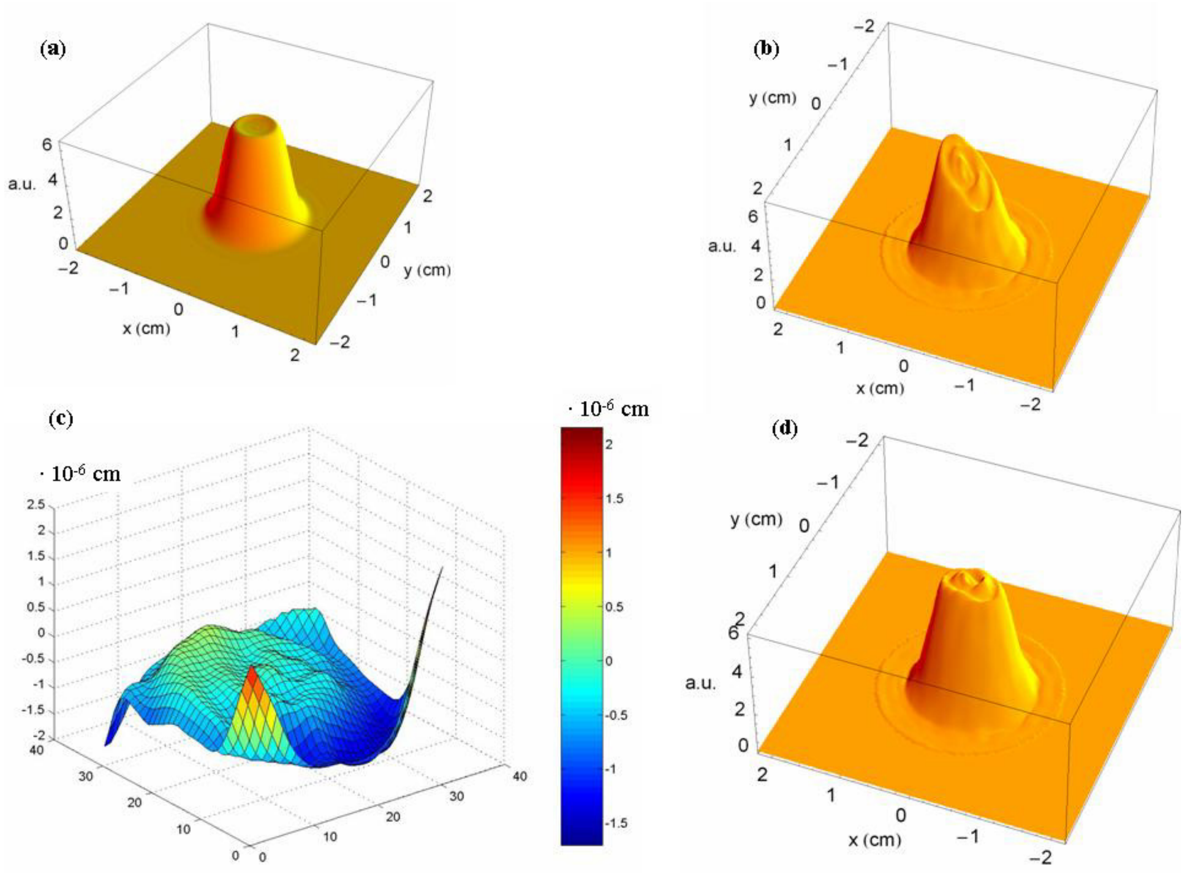

Figure 4 (a) Simulation with ideal MH profile, (b) simulated resonant beam resulting by the implementation of the 5008 test mirror, (c) Difference between the 5008 test mirror's profile and the ideal mirror profile (d) simulated beam with corrective tilt.

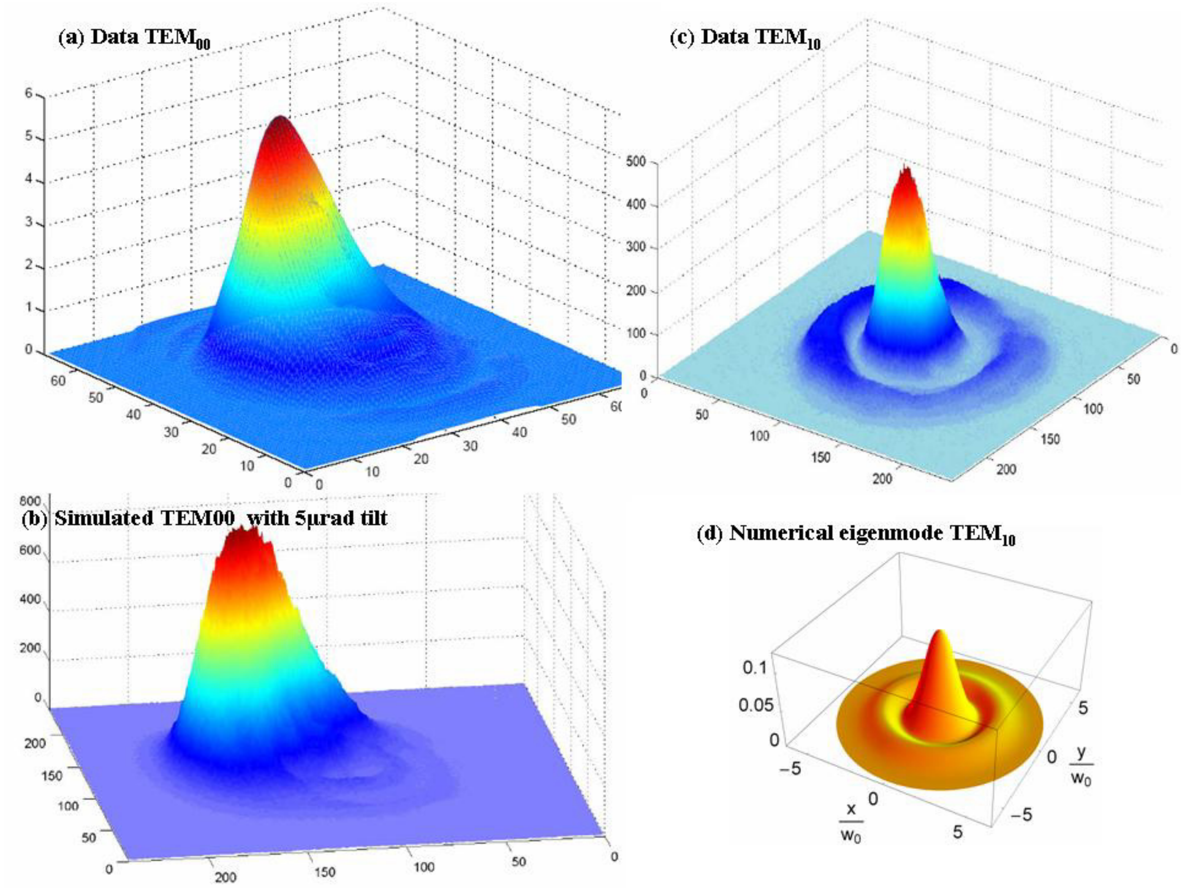

Figure 5 (a) Data for the TEM00, (b): Simulations for the TEM00 with tilt; (c) TEM10 experimental profile; (d) TEM10 numerical eigenmode for MH Fabry Perot.

8. Acknowledgements

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