Design and realization of components based on free-form optical elements

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Until now the manufacturing of precision optical systems has been impeded by two factors, the lack of automation in the manufacturing process and the limitation imposed on optical designs due to the lack of truly free-form optical elements. Both of these factors can be addressed through the use of free-form machined optical elements. The performance of optical components based on conventional rotational symmetric optics can often be improved and the number of elements involved reduced through the use of free form elements. Also the ability to implement alignment features into the components can lead to a significant reduction of the complications and costs throughout the assembly process.

Optical Design

The work reported in this paper shows how the performance of an optical design based on a single free-form optical element can be used to compensate astigmatism in an optical system. Lenses have been designed and fabricated to illustrate the lens performance when compensating for astigmatism in different optical systems. Traditionally, collimation and astigmatic correction of laser diodes can be achieved by implementing two cylindrical lenses. We combined the two cylindrical lenses in a free-form optical lens design with the surface sag generally described as

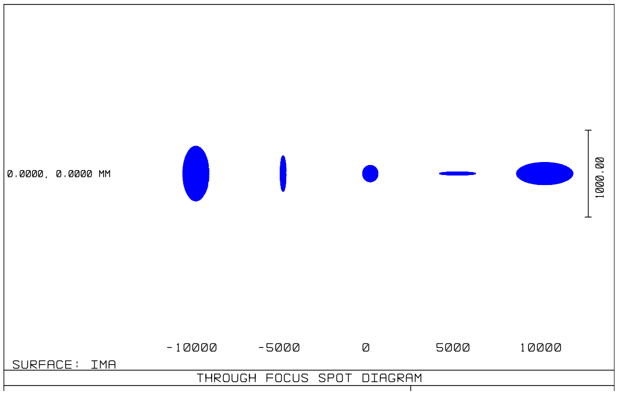
$$sag = \frac{1}{R}\frac{x^2+y^2}{1+\sqrt{1-(1+c)\frac{x^2+y^2}{R^2}}} + \sum_{i=1}^{N} A_i E_i(x,y)$$

where R is the lens radius, c is the conic constant, N is the number of polynomial coefficients, and A_i is the coefficient on the i^{th} polynomial term. The polynomials are simple power series in x and y. For illustrative purposes we consider substitution of two cylindrical lenses with a single free-form lens consisting of two perpendicular parabolic surfaces, while other possibilitites for optimization through the use of higher order polynomials terms are neglected. In this case the free-form surface sag is

$$sag = A_1x^2 + A_2y^2$$

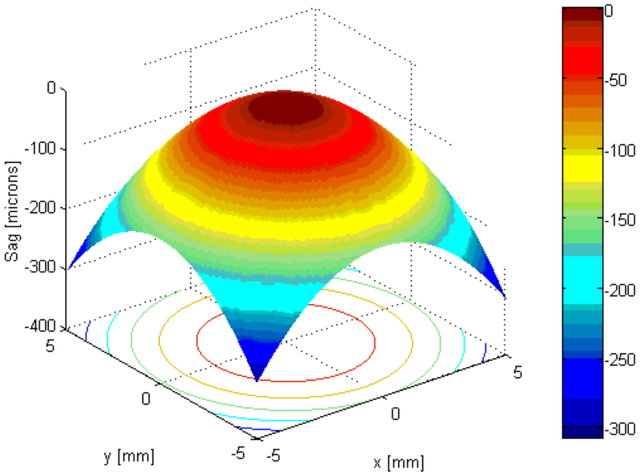
where c=-1, R=∞, and N=2 has been used.

An astigmatic optical system can be compensated by this type of free-form lens. Consider a system having an astigmatism of 7.9 mm, i.e. the system can be considered as two sources displaced by 7.9 mm along the optical axis. A free form surface with $\frac{1}{A_1} = -126.82mm$ and $\frac{1}{A_2} = -134.61mm$ illuminated by a collimated light beam revelas a line of focus on each side of the lens focal length (130mm) as illustrated below

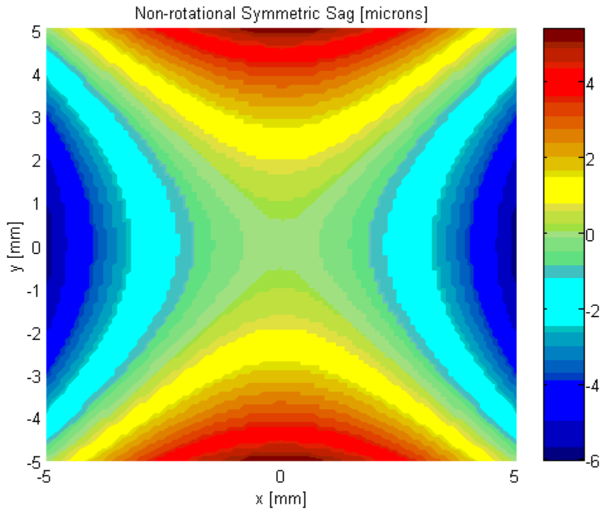


Spot size characterization through focus of the

A circular spot is observed at a distance of 130 mm, whereas perpendicular line-foci are observed on each side of the plane of focus (all figure units are in um). The surface sag of this free form lens is $300\mu m$ whereas the modulation from best fit sphere is only about $\pm 5\mu m$ as illustrated below.



Sag of free-form lens



Non-rotational part of the surface sag

Fabrication

Through the use of an ultra-precision cnc-controlled multi-axis machine (Moore Nanotechnology System FG-350), we have manufactured a series of components based on the suggested optical design. The components were free-form single point diamond turned by phase-locking two linear axes of movement with the rotation of the work piece spindle during diamond turning in inverse-time programming mode.

In order to achieve optical elements of very high quality, the part programming of the machine is carried out in an iterative scheme enabling us to remove any reproducible errors in the optical elements that might be present when the machine is operating in a truly free-form mode. The form-error and surface finished of the free-form diamond turned components are analysed and the performance of the optical system is evaluated and compared to the optical design.

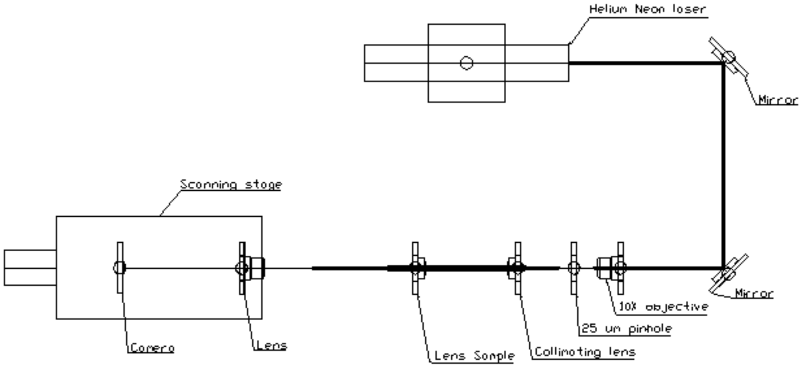
For cnc-programming of the machine a software package has been developed which enables conversion of optical designs made in Zemax into cnc-code, with user defined process parameters such as diamond tool radius, C-axis increment, infeed, depth of cut and number of rough and finish cuts. The lenses were processed with a C-axis increment equal to 1 degree and an infeed equal to 0.001mm/rev. With a diamond tool having a radius of 500μm the infeed leads to a coherent noise on the order of

$$C_{noise} \approx R_{tool} - \sqrt{R_{tool}^2 - \left(\frac{Infeed}{2}\right)^2} \approx 0.3\ nm$$

and the C-axis increment of one degree, corresponds to a maximum distance between data points of 87 μm. along the spiral toolpath, for the maximum part radius of 5 mm. The lens material is Acrylic. The given process parameters and the easy convertion of the optical design to cnc-programming leads to a relatively short cycle time.

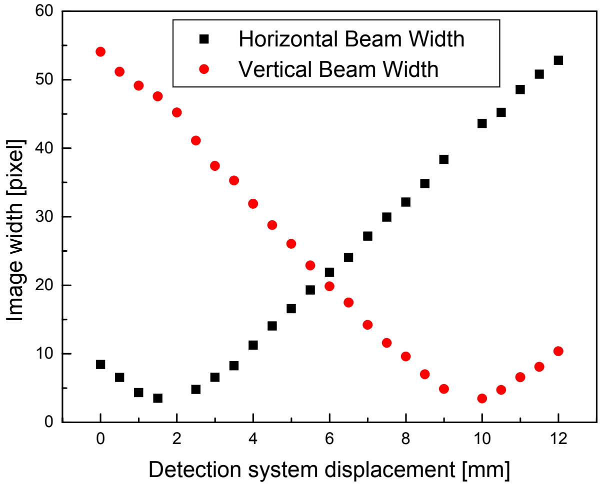
Testing

A Helium-Neon laser is used to measure the astigmatism of the produced lenses. The optical setup is illustrated below. The light from the laser is spatially filtered and collimated before impinging on the lens under test. A lens of short focal length is used to magnify the generated beam focus onto a ccd-camera. The magnifying lens and the camera are placed on a tranlation stage, enabling us to measure the generated astigmatism.



Schematic diagram, of setup for measuring astigmatism

The measured profile of the beam generated by a 7.9 mm astigmatic lens is shown below



Horizontal and vertical beam width (1/e^2) versus

Conclusion

We have shown that through the use of a high precision multi-axis cnc-machine we can manufacture free-form lenses enabling us to generate - or compensate - astigmatic beams. The entire process from optical design of the free-form surface, over the programming of the machine, through the actual part machining and final testing has been discussed. Based on the suggested concept of optical asticmatic lens design, a well-known astigmatism in a system can be compensated by implementing a single free-form lens. Here we have considered the simple case of a surface described by only two parameters (the curvature in two directions) in general higher order terms can be included in order to obtain better performance of the optical system.