The self-mixing interferometer setup modeled by optical soft

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***Abstract* — The capability to model optical instrument prior to detailed design and analyses is very powerful tool that can save schedule time, instrument implementation costs, and gives great insight into many facets of optical instrument development effort leading to better innovations. Optical engineering software has the capability to model the completed self-mixing interferometer (SMI) from laser diode as a light source through the optical components up to the photodetector. The peculiarity of the SMI is that the sample under test has to be included in the optical scheme consideration as a reflective optical component. Every time changing object the optical properties of SMI must be optimized.**

Modeling of SMI which consists of off-the-shelf components like as an aspheric lens and anamorphic prisms was carried out. The first step in modeling an optical system was creating an accurate geometrical model. Collimated beam is important feature for vibration measurements as object displacement leads to change the value of object surface reflection caused by no good collimated laser beam. The purpose of analyses and optimization is the modeling of the SMI optical system which gives collimated beam of laser diode. Optical soft analyses like 3D layout, spot diagrams, relative illumination and coherent irradiation have been under consideration. Another intended benefit of the SMI modeling by optical soft is the signal detection and processing area. Based upon the power, irradiance, or other radiometric based measurement the SMI can provide signal level information.

***Index Terms* — self-mixing interferometer, optical engineering software, laser diode.**

I. INTRODUCTION

Recently, various nondestructive optical measurement methods have been proposed to remotely measure micro/nano-displacement, distance, velocity and etc. [1–3]. In these sensors, laser diode self-mixing interference played an important role. SMI, also known as optical feedback or injection interferometry, is a promising technique for a variety of measurement applications involving interferometry. Using a laser diode (LD) with an external cavity as interferometer, the technique offers several advantages over traditional interferometric configurations, such as Michelson, Mach-Zehnder and Sagnac. SMI setup is much simpler than conventional interferometers because many optical elements such as the beam splitter, reference mirror are not required, compact and part-count-saving. Moreover, it does not require an external photodetector, because the interference signal can be picked up by the monitor photodiode of the LD package. Based on SMI, many smart and simple laser sensing systems have been developed. From the optical point of view the self-mixing interference was used to measure the displacement with accuracy the fraction of $\lambda/2$ by counting the interference signal peaks. In order to increase the measurement accuracy beyond $\lambda/2$, some methods for analysis of SMI signal have been reported [4]. For example, in optical path length measurements, the technique offers subnanometer sensitivity, limited by the quantum detection regime. Finally, the use of laser light also allows remote measurements [5].

The use of LD as a light source in optical devices and general illumination offers significant advantages concerning power consumption, lifetime and color management. However, LDs driver and temperature and thermoelectric cooler controller are still relatively expensive. Therefore, the first task of the designer is to deliver all the light into the system. Analysis of available solutions shows, that non-imaging optics outperforms its imaging counterpart in collimation of extended sources. However, in contrast to well-known design approaches of imaging optics, design algorithms of non-imaging optics are often very sophisticated and some of them are even patented.

Optical design usually begins with simple considerations of the spatial envelope of a new lens – finding the object/image distances and sizes, aperture, focal length etc. The designer must then find a suitable starting design, either derived from basic theory, from his experience or from a design library. This start point will need to be analyzed and understood and then optimized to match the requirements of the task in hand. Almost always, optimization involves repeated simultaneous multi-variable adjustments, and this therefore requires sophisticated software tools.

The key technology in imaging optical design is automated optimization. The designer has to provide a reasonable initial system prescription and a merit (or error) function for estimation of system performance. .

Throughout the long history of design of image-forming optics correspondence between image quality/energetic performances and simple geometrical parameters like spot radius as a deviation of the ray incidence coordinates from the chief ray coordinates or wavefront deformations as an optical path difference was used. It's sufficient to trace a small number of rays to determine the system performances. Moreover, such merit functions are continuous with respect to almost all the system parameters.

The edge ray principle used to be the workhorse in design of non-imaging optics. Most of the developed algorithms use it for sequential tailoring of image surface profiles, but direct implementation into commercially available optical design software is comparatively uncommon.

To design a SMI, the optical system for collimating and focusing of laser beam has to be analyzed. Analytical models of SMI have already been reported [4, 5]. However, they are based on wave optics and not convenient to use in design process. In this paper, we propose a ray–tracing implementation of SMI modeling. In modern optical system design, ray tracing software packages are frequently used because they provide more functionality and flexibility with various analysis and optimization features, which makes the design process much more efficient and reliable.

Usually the external optical system of SMI consists of two lenses in accordance with two aims: to collimate and focus the laser beam. The simple optical system allows focusing the laser beam on only one point at the object under test. Moreover this point is strictly fixed at the optical axis. During the object displacement along the axis the spot diameter changes which leads the error caused by optical system precision over information about object surface. In this way mechanical properties of the object will be measured with an error.

In the report we propose one possible way to resolve this problem. We have developed design tools and algorithms for optimization of non-imaging system of SMI within the optical design program ZEMAX®. These include optimization of optical set-up according to the edge-ray principle as well as direct optimization to obtain prescribed light distributions.

We present illustrative examples to demonstrate the design capabilities, focusing on the optimization of aberrated systems, discuss advantages and limitation of our ray-tracing implementation.

II. OPTICAL SET-UP AND DESCRIPTION OF SMI MEASUREMENTS

Figure 1 presents the schematic arrangement of the SMI, consisting of a laser package with the laser cavity enclosed by the laser mirrors M_1 and M_2, a monitor photodiode and an external reflector, M_{ext}. Light emitted by the laser is guided to the external reflector, which reflects it back to the laser cavity, where this reflected light interacts with the original laser light, producing an intensity modulation in the output of the laser light. Intensity modulation caused by a movable external reflector is similar to that produced by a conventional optical interferometer, such that the fringe shift corresponds to an optical displacement of $\lambda/2$ [3]. The interference signal is detected using a monitor photodiode located at the backside of the laser cavity.

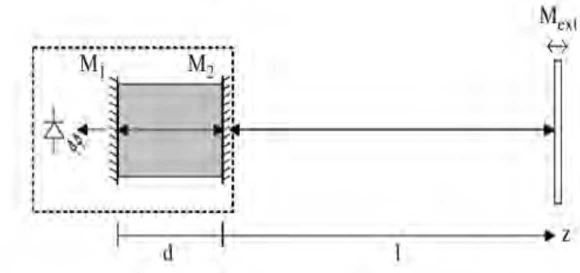

Fig. 1. Schematic arrangement of the SMI.

According to the theory, mirror M_2 is replaced with an effective mirror, which combines the laser cavity and the external cavity to form a compound cavity. The amplitude reflection coefficient of the effective mirror r_2 is

$$r_2(\nu) = r_{2s} + \left(1 - |r_{2s}|^2\right) \cdot r_{2ext} \cdot \exp^{-j2\pi\nu\tau_{ext}} , \qquad (1)$$

where r_{2s} and r_{2ext} are the amplitude reflection coefficients of laser mirror M_2 and external target M_{ext}, respectively. The optical frequency is **ν** and τ_{ext} corresponds to the round trip delay back and forth through the external cavity, $\tau_{ext} = 2L_{ext}/c$, which is assumed to be air in this case; c is the speed of light. To archive successful data operation of the laser, both the phase and amplitude conditions must be fulfilled. The phase condition states that the round trip phase of the compound cavity must be an integer multiple of 2π.

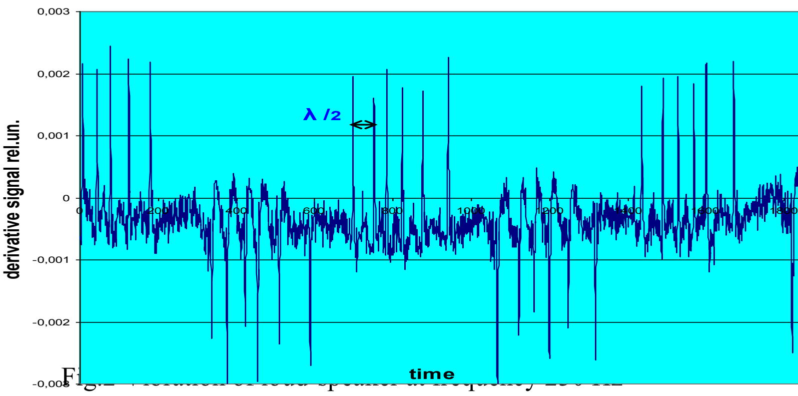

Fig.2 Vibration of loud speaker at frequency 250 Hz

III. THE OVERALL ANALYSIS PROCEDURE

The requirements for the optical measurements are derived from the SMI system specifications. Our aim is to understand the optical system performance integrally. But first with optical code, we have capability to design the SMI assembly by building the geometrical model piece by piece and assigning to each piece the correct position and optical properties. It is important for each piece to have the correct position and optical properties so that each part of the geometrical model can interact with the light, by reflection, refraction, transmission, scatter, and diffraction, which are incident upon it.

Optical design code ZEMAX is the geometrical ray trace simulation program that can apply a mathematical optimization algorithm to determine an optimal optical components design for a given set of conditions. While performing and evaluating geometrical ray traces, the lens design code changes element radii of curvature, thickness, spacing, and refractive indices, forcing the optical system to conform to a certain merit function.

There is shorter way of set-up design for customer. Now it is possible to design the virtual optical set-up based on off-the-shelf components files with description of all optical properties from vendors before purchase. The file is created by the original designer, and is then sent, usually as part of a complete "playback" ZMX code lens file, to the end customer. The complete ZMX file from vendor allows the customer to made geometrical model, rays tracing and, finally, to verify the optical design performance. This shorter way was chosen in our design approach.

The other important feature of ZEMAX is the capability to introduce and assess the properties and performance of source of light, in our SMI laser diode. Optical properties of laser diode such as analysis rays, power, astigmatism, X, Y-divergence, X, Y- supergauss need to be pointed in non-sequential editor for rays tracing. The user interface is common to both sequential and non-sequential ray-tracing as editor spreadsheet. Almost all data is entered via editors, which allow the parameters defining the optical system to be easily seen, and linked together or optimized as required. Note that the Lens Data Editor shows a sequence of 'Standard' surfaces which have radius of curvature, thickness, glass type, semi-diameter and conic constant of components based on the ZMX lens file.

We have imposed an additional requirement for the program – that redundant optical measurements are required for each important parameter. We're now going to insert ZMX files of components. Think of the automated lens design process as a feedback loop. Optical design code is efficient at finding solutions to this type of problem.

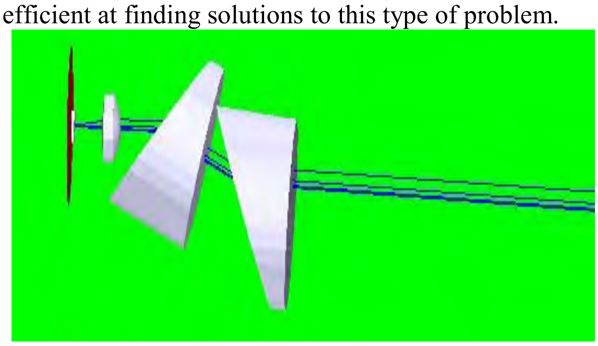

Fig. 3. The geometrical shadow model of self-mixing set-up with anamorphic prism beam pair after analyses and optimizations. 100mW laser diode with BK7 glass window of 0.25mm thickness in front, aspheric lens CAY-046 from Thorlabs, and two anamorphic prisms have shown. Well collimated LD beam is obtained.

Optical design is only one part of product design. To work out the completed product the designer needs to export the optical component holders from optical code files into mechanical design package. Thereby after analyses and optimization of the optical set-up the next step for making-up device is the mechanical package producing.

ZEMAX imports data from CAD programs via the IGES, STEP, SAT and STL formats, and exports data in the same formats. This allows simple and fast exchange of design data between ZEMAX and mechanical design 3D CAD packages. Moreover ZEMAX supports the ability to perform Boolean operations on volume NSC objects. This feature consists in such operations like pooling objects together, subtracting one object from another, or defining an object as the intersection volume of two objects. The resulting trimmed object may have thin-film coating, scattering and diffraction properties assigned to each resulting face independently. In this way the mechanical design packages can be made by more easy method with sequence drawings of the device. The surface scattering properties of a parent object which is always important for interferometer are inherited by the Boolean object too. The Boolean object allows up to ten parent objects to be combined in any series of Boolean operations to provide a parametric object. In practice this option is enough for mechanical design of any support of optical component then exported as a CAD-format object. Both sequential and non-sequential optical systems are exported to CAD. Thanks to the general 3-D nature of CAD objects, they can be imported in non-sequential mode only, but ZEMAX's flexible hybrid-mode non-sequential ray-tracing allows sequential optical systems to trace transparent, others may be reflective, and others scattering. ZEMAX makes it easy to 'paint' optical finishes onto the different faces of a CAD object.

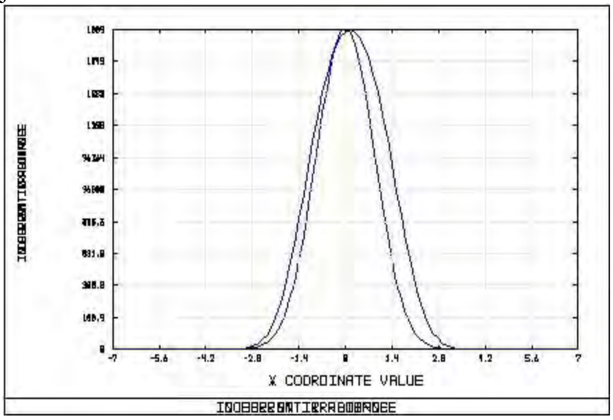

Fig. 4. Coherent irradiance vs. coordinate value in X-Y directions in object plane is overlaid. Good coincidence of Gaussian beam X-Y dimensions is obtained. The X-coordinate of drawing is numbered in mm.

Geometrical model of self-mixing interferometer consists of 100mW LD, an aspheric lens and two anamorphic prisms. Laser has glass window in front of the diode crystal was included in set-up for correct ray-tracing. A can-type LD is the simplest commercial packaging for laser diode. It consists of the actual diode, a photodiode for monitoring output, and the can that holds them. A photodiode uses for interference registration in SMI. LD poses special challenges because its output is irregularly shaped (elliptical). It is difficult to compensate elliptical beam with a single lens and therefore the best lens will depend on the specifications of LD (for example, the beam divergence in axes) as well as the desired beam characteristics (e.g. desired spot form and focusing distance). In many cases, the desired results can only be obtained with multiple elements. Fortunately, if the main concern is beam quality without the need for a custom multiple-element solution, aspheric lens offers good solution to maximize the quality of the LD beam.

Aspheric lenses collimate light without introducing spherical aberration into the transmitted wavefront. For monochromatic sources, spherical aberration is often what prevents a single spherical lens from achieving diffraction limited performance when focusing or collimating light. Thus, an aspheric lens is often the best single element solution for collimating the output of a LD. This lens utilizes molding technology to produce a near diffraction-limited optics including LD window correction and enable a reduction of set-up lens elements. Molded plastic glass aspheric lenses are ideal for many applications in particularly as application requiring a lower cost design.

Anamorphic prism pair specially designed for circularizing LD beam for a large variety of LD elliptical beam profiles. The elliptical beam profile of LD often has to be made circular for many applications. Anamorphic prism pairs can be used to circularize an elliptical beam, in other words, to expanding or compressing one of the beam axes. As each LD exhibits its own individual beam ellipticity, adjustable rather than fixed prism pairs are required to achieve good circularity. Such prism pair allows adjustment of both prisms inside the mounting, resulting in a variable magnification between 2 & 5 of one axis. A near circular beam was attained by properly aligning of prisms to appropriate magnification ratio.

At first was selected the "Beam Definition" tab. The beam type is Gaussian and the (radial) waist size in both X and Y is 0.004 mm (4 microns). The beam is set to start at surface 1 (LD) and is propagated to the image surface (6). Option the "Separate X, Y" is chosen . This option allows for greater accuracy when propagating anamorphic beams. Turning this option on results in ZEMAX using separate phase references in the X and Y directions.

Note, that while the input beam is a anamorphic Gaussian beam (with a waist of 4 microns), the output beam is rotationally symmetric as a result of the propagation through the anamorphic prisms. The pilot beam is a best-fit Gaussian beam. The fit is generated based on the actual wavefront parameters. To perform a more detailed analysis of the anamorphic beam is used Detector Viewer cross section plots (Fig. 4). To make a cross section plot, on "Settings" from the menu bar of this window was chosen “Smoothing -6”, “Coherent Irradiation”, “Cross-section Column”. After analyses and optimization (via angles of prism rotation and positions) the relative illumination in image plane was calculated (Fig. 5). To make this surface plot, on "Settings" from the menu bar of this window was chosen “Smoothing -7”, “Detector Surface 6”, “Sampling 128x128”.

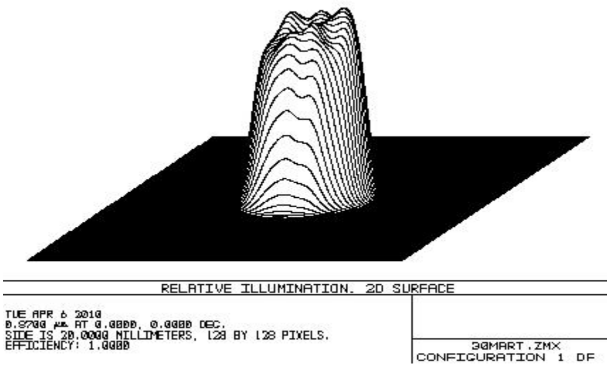

Fig. 5. Relative illumination in image plane is shown. The total width of the detector (black square) is equal to 20x20mm. The detector size is divided into pixels according to the sampling setting 128x128pxs.

IV. CONCLUSION

This paper has discussed how to design self-mixing interferometer with anamorphic system in ZEMAX. The main points are: ZEMAX provides a wide range of tools for studying both geometric and diffraction effects in these components. The design is optimized using usual mixed sequential/non sequential ray-tracing techniques, for best spot size, a required collimated beam, magnification, image location etc. The source is assumed to be a uniform, circular plane.

We have proposed the new approach for design of optical part of SMI which consists in ZEMAX optical code application. As the result of analyses and optimization of the SMI optical system the positions and orientations of optical components for collimated beam of laser diode were determined. This design of components is intended to produce a collimated beam, with the equal spatial extent in X-Y and the smallest angular divergence along Z axis.

Optical soft analyses like 3D-layout the geometrical model of interferometer, spot diagrams, relative illumination and coherent irradiation have been under consideration.

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