Design and simulation of GRIN objective lenses for an imaging fiber based speckle metrology system

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ABSTRACT

Gradient-Index (GRIN) lenses are characterized by its small diameter and length, enabling them to be an effective lens for an integrated probe based imaging system. For a speckle-based surface metrology system, the imaging lens plays an important role in deciding the statistical dimensions of the speckles. In such cases, the design and simulation of the lens system would be a key process to better the performance of the lensed imaging fiber probe. In this context, this paper focuses on the design of lensed fiber probes for a speckle-based surface metrological imaging system that can find intra cavity interrogation applications. Different optical properties of GRIN lenses and imaging fibers are considered while designing the final probe distal end to meet the targeted specifications. Singlet GRIN lens configuration is analyzed for a front view configuration and a parameter optimization has been carried out to obtain the specifications including the field-of-view, resolution, working distance and magnification.

Keywords: Fiber optic metrology, Speckle imaging, GRIN lenses, ray trace simulation.

1. INTRODUCTION

In the modern manufacturing industry, The measurement of surface roughness plays an important role to achieve the desired surface quality of the metal parts. Various machining processes carried out on these metal parts induce surface roughness variations, which can be controlled by continuously monitoring the average surface roughness (Ra) of the surface. Among the various methods for surface roughness measurements, optical methods are characterized by its non-contact and high-speed measurement capabilities[1]. Recently, there has been an increased interest in speckle-based surface metrology systems due to its inherent simplicity and its capability to measure a wide range of roughness values [2-6]. Speckle-based metrological systems are also capable of measuring wide surface area dimensions, from a micrometer scale to a meter scale. For a speckle-based surface metrology system, the imaging lens plays an important role in deciding the statistical dimensions of the speckles [7-9]. In such cases, the lens design and simulation would be a helpful process to improve the performance of the imaging fiber probe. Since the overall diameter of the probe is required to be in the range of 1mm based on the target specifications, miniature optics are required for the imaging probe design. One option to achieve the target is to use Gradient-Index (GRIN) lenses since their diameter can be reduced down to a range of 0.5 mm without facing any fabrication difficulty[10]. GRIN lenses guide light through a refractive-index variation in a direction perpendicular to the optic axis. The variation in index of refraction is generally achieved through ion exchange process and custom fabricated GRIN lenses as per the design requirements can be obtained from various companies. In this paper, a miniature probe based speckle metrology imaging system is designed and simulated using Zemax simulation software[11]. The optical properties of the GRIN lens and the imaging fiber is considered while designing the probe distal end to meet the specifications of speckle imaging probe. A GRIN lens in a singlet configuration is analyzed in a front-view configuration and a parameter optimization has been carried out to meet the design specifications such as the field-of-view, resolution, working distance and magnification.

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2. DESIGN METHOD

The design methodology is based on conducting ray tracing simulations that considers both engineering design and optical design requirements of the imaging probe. The lens system and the imaging fiber is considered as a single entity at the distal end of the probe as shown in the schematic Figure 1.

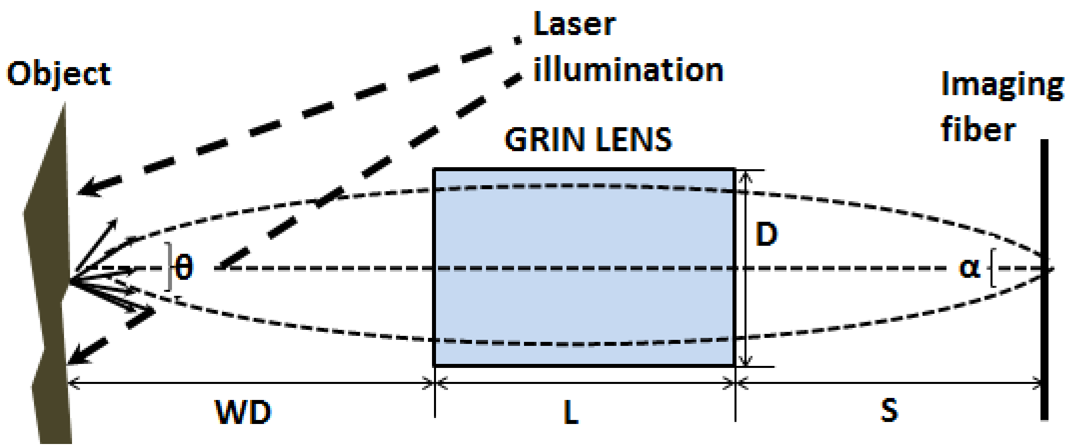

Figure 1. Schematic diagram of GRIN lensed speckle imaging system

2.1 Numerical Aperture (NA) requirements

The Numerical Aperture (NA) in a fiber based imaging system can be divided into Object Space Numerical Aperture (NA_{Obj}) and Image Space Numerical Aperture (NA_{Img}). The NA_{Obj} decides the light collection efficiency from the object space and it is related to the half angle (θ/2) of the light cone at the object space, which determines the resolution. Whereas, NA_{Img} is related to the half angle (α/2) of light cone at imaging fiber end. The NA_{Img} determines the light coupling efficiency to the imaging fiber, which determines the distortion. For a normal imaging application, the NA_{Obj} should be maximised and NA_{Img} should be minimised for a better imaging performance. Since the speckle imaging in the probe is in a Fraunhofer arrangement, the object space resolution and NA_{Obj} have least significance in the speckle imaging probe design. Whereas, NA_{Img} should be minimised to a low value considering the imaging circle diameter of the fiber. For a typical imaging fiber with 10000 elements the imaging circle is ~325 µm and $NA_{Img} < 0.3$ is targeted for a better field balanced performance.

2.2 Magnification (M)

For a subjective speckle imaging system shown in Fig.1, the average speckle size is given by the following relationship [12],

$$\delta = \frac{1.22\lambda(1+M)S}{D} \tag{1}$$

Where, M is the magnification of the lens, S is the image distance and D is the diameter of the lens. For a paraxial ray approximation, Eqn (1) can be modified as shown below

$$\delta = \frac{1.22\lambda(1+M)}{NA_{\mathrm{Im}g}} \tag{2}$$

Where, NA_{Img} is the image space numerical aperture at the imaging fiber. The average speckle size that can be resolved by an imaging fiber is determined by the specified fiber spacing. For example, in an FIGH-10-350S Fujikura fiber, the spacing specified is ~4.3µm. In order to resolve the speckles at the imaging fiber, the imaging lens should have a magnification M, which gives an average speckle size greater than the fiberlet spacing of the imaging fiber. For instance, setting δ=4.3 µm and NA_{Img}=0.3 in Eqn (3) gives a magnification M= 0.67, for a wavelength (λ) of 632.8 nm. This elucidates the requirement of magnification $M \geq 0.67$ in such imaging fibers so that the speckles are completely resolved.

2.3 Diameter (D)

The diameter of the probe is considered here bearing in mind the potential of the probe for interrogating technical cavities with diameter less than 1.3 mm. Assuming that there will be separate illumination fiber in such probes, the designed probe should consider the dimension of the probe distal end not to exceed 1 mm.

2.4 Working Distance (WD)

The working distance (Object distance) is the distance from the front surface of the lens to the object under inspection. A shorter focal length yields a shorter working/focusing distance and a higher magnification. For the speckle metrology system under consideration, a shorter working distance is desirable for the miniaturized sample under investigation. Considering the diameter constraints of 1mm, a front view probe should have a WD ranging from 300µm to 10mm to measure inside the wide range of samples under investigation.

2.5 Field-of-View (FOV)

The Field-of-View describes the diameter of the observable area in an optical probe. The FOV is very important for speckle imaging applications as it determines the amount of processable data for a statistical image analysis. For a selected imaging fiber, FOV is determined by the magnification of the micro lens assembly. To get a large FOV, micro lens assembly should be designed such that a demagnification is achieved. Another approach for obtaining a large FOV is to design a wide angle micro lens assembly. The design challenge here is to acquire the appropriate FOV with respect to working distance for each sample without compromising on the resolution. Considering the dimensional constraints and statistical data analysis requirements, a minimum FOV of 0.3mm is set for the probe.

With respect to the above criteria for a speckle imaging probe, the optical design requirements are listed in Table.1

Table 1. Design requirements in GRIN lensed speckle metrological probe

Design parameter	**Value**
WD	≥0.3 mm
NA_{Img}	<0.3
M	≥ 0.67
FOV	≥ 0.3mm
OD	0.5mm
Λ	632.8nm

3. DESIGN RESULTS

3.1 Singlet GRIN objective lens

The lens performance is analyzed using the ZEMAX software. The material catalog SGRIN.DAT from GRINTECH GmbH company has been imported into the Glass catalog database of Zemax software to simulate GRIN lens assemblies. This will help us in purchasing the customized imaging assemblies from the same company. The first step in the design process is to consider the GRIN lens objective as a finite conjugate optical system, wherein both the object and the image are located at a finite distance from the lens. With respect to the design parameters described in Table.1, various lens objectives are simulated for different WD varying from 0.3mm to 3mm. Figure 2, shows the ray diagram and the spot diagram for a WD=0.8mm. A diffraction limited performance is observed at this WD for the field points considered. The RMS spot sizes are within the Airy radius dimensions for all the three fields, h=0mm, h=0.06mm, and h=0.125mm.

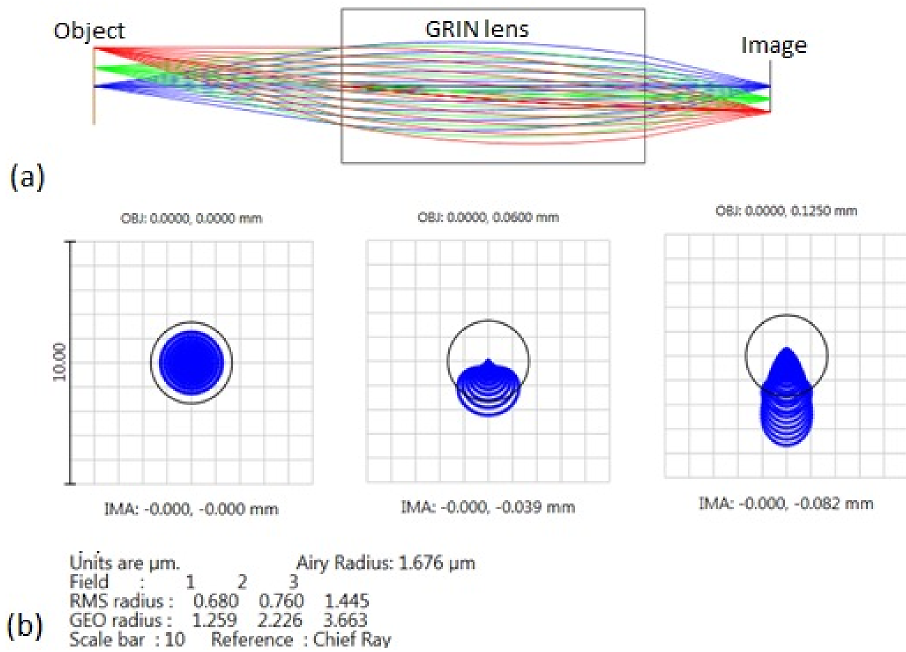

Fig.2. (a) Ray diagram of singlet GRIN objective lens at WD=0.8mm (b) Spot diagram for three fields corresponding to object heights h=0mm, h=0.06mm and h=0.125mm

However, the spot diagram shows coma distortion at higher field values as seen in the spot diagram for field point 3. Distortion increases with higher field points due to a lateral shift of rays. The distortion curve given in Fig.3 (a) shows a percentage of distortion of -1.03% at the edge of the field h=0.125mm. For an image height of 0.5mm, this distortion will result in a 5.2µm lateral shift of the chief ray from its paraxial height. This value is comparable to the fiber-to-fiber spacing of 7 µm in the imaging fiber. This shift has to be reduced to a lower value considering the final image quality required. The Modulation Transfer Function (MTF) in Fig.3 (b) shows a nearly diffraction limited performance for all the fields. The resolution is 275 cycles/mm at 50% MTF for on-axis field and 195cycles/mm for off-axis field at h=0.125mm.

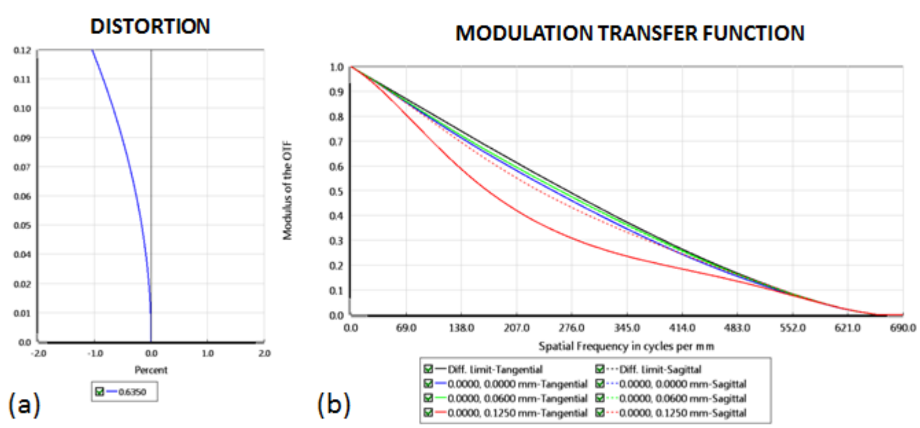

Fig.3. (a) Distortion curve at WD=0.8mm (b) MTF for the three fields h=0mm, h=0.06mm and h=0.125mm

The optimization in probe design is done for varying WD and different optical design parameters explained in Table.1. It is observed that lens length is smaller and a better field balanced performance is observed for higher WD. Table 2 summarizes the simulation results obtained for the different WD of the imaging probe.

Table 2. Simulation results of singlet GRIN objective lens for speckle metrology

WD (mm)	NA_{Img}	NA_{Obj}	Magnification (M)	Lens length L (mm)	MTF at 50% modulation on axis (cycles/mm)	Distortion at field edge(%)
0.3	0.45	0.398	1.17	1.3	96.55	-4.8
0.8	0.23	0.23	0.78	0.87	253	-1.03
1	0.19	0.18	0.68	0.8	220	-0.65
2	0.09	0.06	0.68	0.4	109	-0.08
3	0.06	0.04	0.68	0.27	80	-0.016

The singlet GRIN objective lens can be selected by considering the magnification and the amount of distortion. From the table, it is clear that the smaller WD probe has more distortion and it is difficult to achieve higher MTF through optimization. Considering the acceptable level of distortion and magnification, a WD higher than 1mm is best suitable for the speckle imaging application.

With respect to the different GRIN lens parameters, suitable imaging fibers can be selected for the final probe design. The outer diameter of the imaging fiber is decided by the image diameter formed by the GRIN lens at the image plane. Table 3 explains the FOV, image diameter and different imaging fibers selected from Fujikura with respect to GRIN lens specifications.

Table 3. Imaging fiber specifications for different GRIN lens parameters.

No	GRIN LENS						IMAGE FIBER			
	WD (mm)	D (mm)	L (mm)	M	FOV (mm)	Image Diameter (mm)	No of fibers	Active area (mm)	Outer diameter (mm)	Fiber Name
1	5	1	2.46	0.68	4.66	0.77	30K	1	1.2	FIGH-30-850N
2	5	0.5	1.197	0.68	5.78	0.474	10k	0.325	0.7	FIGH-30-650S
3	1	1	3.23	0.68	0.932	0.312	30K	1	1.2	FIGH-10-350S
4	1	0.5	1.43	0.68	1.154	0.452	10k	0.325	0.7	FIGH-30-650S
5	0.3	1	3.97	1.17	0.28	0.26	30K	1	1.2	FIGH-06-300S
6	0.3	0.5	1.84	1.17	0.28	0.23	10k	0.325	0.7	FIGH-06-300S

4. CONCLUSION

The GRIN objective lenses are designed and the performance is evaluated for fabrication of optical fiber based probes. It has been observed that the average speckle parameters are dependent on the imaging lens specifications and a proper design in combination with a lens selection guideline is required for the final probe design. In order to resolve speckles properties through an imaging fiber, the lens system should have a specified image space NA and magnification. Even though a shorter WD can provide higher magnification, these GRIN lenses are characterized by a higher distortion in imaging. Considering the FOV requirements and distortion factor, a WD greater than 1mm is best suitable for the speckle imaging application. A representative table has been shown depicting different GRIN lens parameters and imaging fiber specifications for the final probe design consideration. It is envisaged that the study and analysis conducted here can enable design and fabrication of suitable optical fiber probes for speckle metrological and other imaging applications.

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