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Research activities in optical metrology at IIT Madras (India) during 1971-2000

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Dedicated to Prof (Dr) Daniel Malacara-Hernández

Some of the research activities carried out by the Author and his group during 1971-2000 at the Applied Optics Laboratory, IIT Madras (India) have been described. These include improved collimation testing methods, measurement of long radii of curvature and focal length, multiplexing in speckle interferometry, measurement of displacement, slope and curvature using ESPI/DSPI and many more other measurements.

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1 Introduction

I am extremely happy to write a short essay on our activities in the field of optical metrology for a special issue of Asian Journal of Physics to recognize Professor Daniel Malacara Hernandez for his vast contributions to this field. Prof Malacara is known to me through his work for almost 40 years, and we were benefitted by learning from his research papers and particularly the book '*Optical Shop Testing*' which has referred several of our research papers.

Having completed my Ph D in Physics in June,1970 under the guidance of Prof M S Sodha from Indian Institute of Technology Delhi (India) and serving the department of Physics for a short period as lecturer, I joined the Fine Technics Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras (IIT Madras, India) in March 1971 as an Assistant Professor. IIT Madras received technical, academic and financial assistance from the German Government. Hence, technical optics (Technische Optik) was a discipline in Fine Techniques Laboratory, Department of Mechanical Engineering. Fine Technics Laboratory comprised of Technical Optics, Fluidics, Controls and Engineering. Technical Optics section was equipped with optical workshop, vacuum coating unit, metrology laboratory and large number of optical components. Metrology laboratory contained Universal Measuring Microscope, Camshaft testing equipment, hardness tester, Focometer, profile projector, Twyman-Green Interferometer and He-Ne laser (Spindler and Hoyer). When I joined the Laboratory, there was a German Professor, Dr Bantel, one Lecturer, Dr M P Kothiyal, and one optical technician in the technical optics section of the laboratory. I was tasked to teach a course on mechanical measurements to the B Tech students of mechanical engineering. However, the main thrust was to develop curriculum in Optics and set up laboratory experiments that would be needed by the students in B Tech, M Tech and M Sc. Also, a Ph D program was to be started and that needed courses/programs to be developed to meet the requirements. One major project on the development

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of an aerial camera was also awarded to the Fine Technics laboratory. It was thus obvious that we have to work in three major fronts, namely (i) development of optical devices/instruments, (ii) teaching optics related courses to B Tech, M Sc, M Tech and Ph D students, and (iii) to carry out research work in optics and optical metrology that could be published in refereed international and national journals. To give legitimacy, the optics section was renamed as Applied Optics Laboratory (AOL), which would also become part of the Physics Department after 1979. Unfortunately, AOL does not exist anymore in IITM, Chennai.

2 Optical Instrumentation

An imaging element, be a refractive, reflective or catadioptric, is an essential element in many of the optical instruments that were developed by AOL. Hence, a lens designer was employed as a lecturer. Over twenty-six projects involving many funding agencies were completed out of which 14 projects involved development of optical instruments. Development of optical instruments involved design, fabrication, testing and assembly. Some of the instruments were also commercialized while many were used for specific applications. This activity also supported a few companies which later flourished.

3 Teaching

Syllabi of large number of courses were developed. These included Geometrical & Physical Optics; Interferometry; Optical Testing Methods; Lens design; Holography and its Applications; Speckle Phenomenon and Applications; Optical Data Processing. Some of these courses were supported by laboratory experiments. These experiments were conducted over a period of time and later compiled resulting in a book 'A Course of Experiments with He-Ne Laser' that was published in 1978 by Wiley and has been reproduced in several editions. In fact, 14 books are authored/co-authored/edited in addition to writing chapters for several books.

4 Research Work

Part of our research work can be broadly placed under the following:

1. Enhancing the sensitivity of collimation testing methods.
2. Measurement of very long radii of curvature and focal length – Talbot phenomenon and moiré techniques.
3. Multiplexing: frequency and theta modulation in speckle interferometry.
4. Fringe compensation techniques in holographic interferometry.
5. Displacement, slope and curvature measurement techniques in ESPI.
6. Contouring.
7. Comparative ESPI.
8. Shearography.
9. Array generation.
10. Holo-optical elements.
11. Ion-exchange in glass with the objective to fabricate waveguides.
12. White light speckle photography.
13. Four-wave mixing.
14. Diffraction of singular light at slit aperture.

We will dwell upon a few of the research topics in this write up.

5 Enhancing the sensitivity of collimation testing method

Murty's plane parallel plate has been used for checking the collimation of laser beams [1]. It is placed obliquely in the beam and the interference pattern between the front surface and back surface reflected beams (laterally sheared beams) is observed. At collimation, interference takes place between two laterally shifted collimated beams forming a fringe free field in the overlap area. Strictly an infinite fringe width is observed in a finite aperture plate leading to an error. An improved version of this method requires the use of a wedge plate. The wedge plate can be used in two ways namely (i) shear direction is along the wedge edge and (ii) shear direction is perpendicular to the wedge edge. Usually, the wedge plate is used in which shear is parallel to the wedge direction. At collimation, there is a path difference between the beams reflected from the front and back of the wedge plate due to its varying thickness, resulting in straight line fringes running parallel to the wedge edge. The fringe width in the interference pattern is governed by the angle of the wedge and the refractive index of its material. This method thus requires a fiduciary mark on the wedge plate such that the fringes run parallel to this mark when the beam is collimated. If the beam is not collimated, the fringes are inclined with respect to the mark.

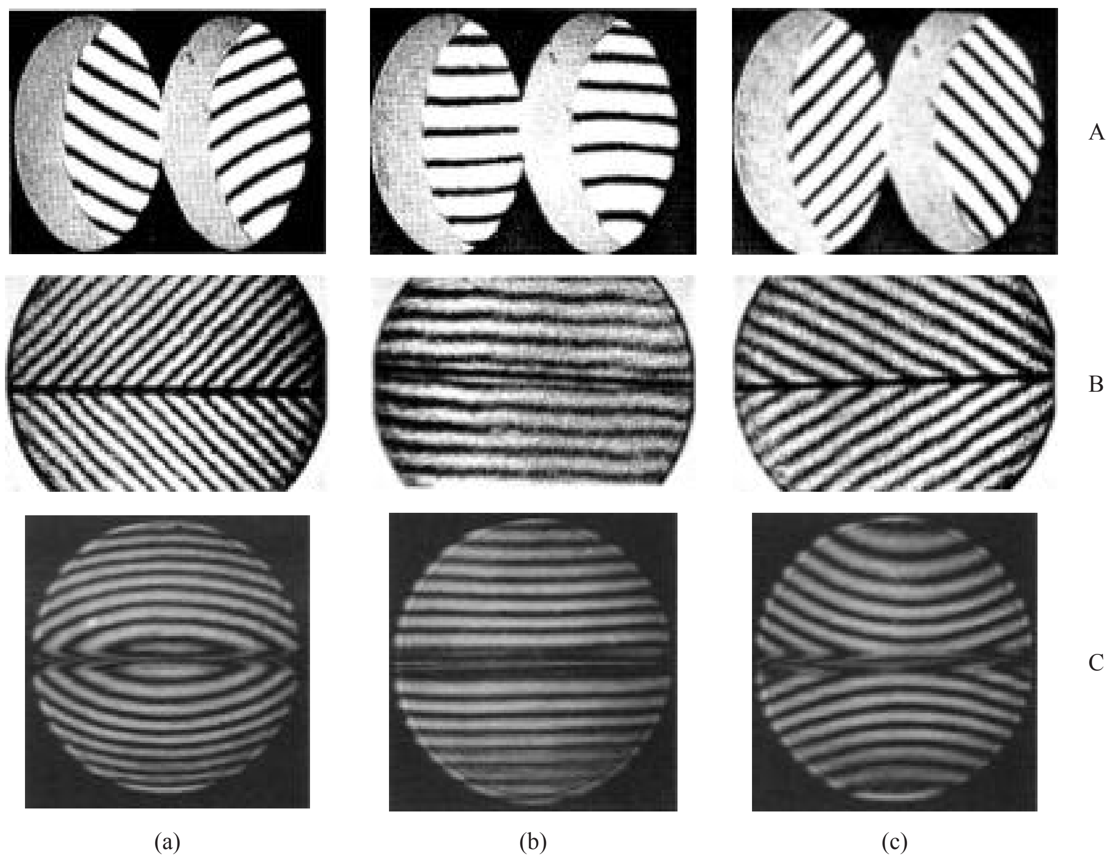

Fig 1. A-Double wedge configuration; B-Composite grating; C-bi-mirror Michelson Interferometer (a) just before collimation; (b) at collimation; (c) just after collimation

Our research eliminated the need of fiduciary mark and also increased the sensitivity by a factor of two [2-8]. We developed two methods- one based on wedge plates [2] and other moiré phenomenon combined with Talbot effect [3]. Both these methods have two variations. In one the fringes make an angle while in the other, the fringe widths are different. The method based on wedge plate uses two identical wedge plates with their angles anti-parallel. When a collimated beam is incident on the pair of plates such that the shear direction is parallel to the wedge edge, straight line fringes are observed which run parallel to each other thus eliminating the need of a fiduciary mark. Departure from collimation results in inclined fringes: the angle between these inclined fringes is twice as large as would be obtained by a single wedge plate thereby enhancing the sensitivity by a factor of two. Figure (1A) shows the fringe patterns obtained with such an arrangement.

However, when the shear direction is perpendicular, the fringe width in the interference patterns obtained with both the wedge plates is same when incident beam is collimated. Departure from collimation lends to different fringe widths in the interference pattern observed in reflection. Figure [1] shows the experimental results of three different methods that provide self-referencing and double the sensitivity. First method utilizes a pair of identical wedge plates placed antiparallel to each other. On collimation, fringes run parallel to the wedge edge and have the same period, i.e. the fringes are parallel to each other in both the wedges. Away from collimation, the fringes enclose an angle. In a second method, a composite grating is used which is self-imaged. At the self-image plane, an identical grating is placed at an appropriate orientation resulting in parallel moiré fringes in the two halves of the composite grating when incident beam is collimated. Away from collimation, the fringes enclose an angle. In a third method, four-wave mixing is used in a Michelson interferometer in which one mirror is replaced by a $BaTiO_3$ crystal and other mirror is a bi-mirror [8]. The interference pattern is due to the superposition of a diverging wave and a converging wave. At collimation, both halves have fringes running parallel. Away from collimation, the fringes curve. There have been other modifications as well.

6 Measurement of very large radius of curvature and focal length

There are large number of methods to measure radius of curvature and focal length of a lens [9-12]. These are best implemented on a bench that is graduated. However, if the radius of curvature or the focal length is very large that cannot be accommodated within the laboratory, special methods are to be investigated. We have proposed several methods to measure long radii of curvature. We describe one of the methods based on moiré phenomenon and Talbot imaging.

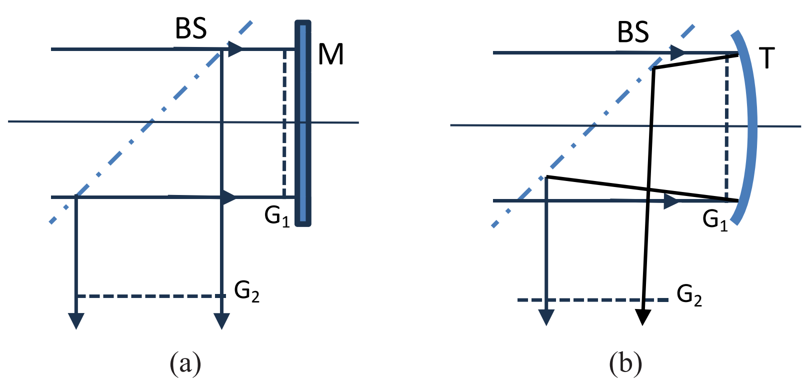

Fig 2. Measurement of long radii of curvature using self-imaging and moiré phenomenon

Figure 2(a) shows an experimental arrangement. A collimated beam illuminates a grating G_1 of pitch *p*. A plane mirror M is placed almost in contact with the grating and the reflected light is deflected by a beam splitter BS. An identical grating G_2 is placed at the first Talbot plane in the reflected beam. The grating elements in both the gratings are parallel to each other. Since both the gratings are in collimated beam and their elements are parallel, moiré fringe of an infinite pitch is formed. Plane mirror M is now replaced by a spherical mirror T whose radius of curvature R is to be measured (Fig 2(b)). The grating G_1, being in almost contact with the mirror, is illuminated by a wave of radius of curvature R. This grating is illuminated by the convergent wave of radius R and hence its first Talbot image will be formed at a distance Z_T, where Z_T is given by

$$Z_T = \frac{2p^2R}{\lambda R + 2p^2} \sim \frac{2p^2}{\lambda}$$

since the radius of curvature R being measured is very large. This means that the location of grating G_2 remains unchanged. Since the grating G_1 is illuminated by a convergent wave, the pitch p' of its self-image will be smaller and is given by

$$p' = p\left(1 - \frac{Z_T}{R}\right)$$

Moiré fringes are formed between the self-image of G_1 and the grating G_2 due to the pitch mismatch. The pitch ρ of the moiré fringes is given by

$$\rho = \frac{pp'}{|p - p'|} = p\left(\frac{R - Z_T}{Z_T}\right)$$

Substituting for Z_T and rearranging, the radius of curvature R is given by

$$R = 2p\frac{\rho}{\lambda}.$$

Better accuracy may be obtained if the grating G_2 is placed at the higher order Talbot planes.

7 Measurement of Long focal length of a lens

Figure 3 shows a schematic of an experimental setup. It follows the same theory that is presented for the measurement of long radius of curvature. The focal length f is given by

$$f = 2p\frac{\rho}{\lambda}.$$

where p is the pitch of grating G_1, ρ is the pitch of the moiré fringes formed due to pitch mismatch and λ is the wavelength of light used for experimentation.

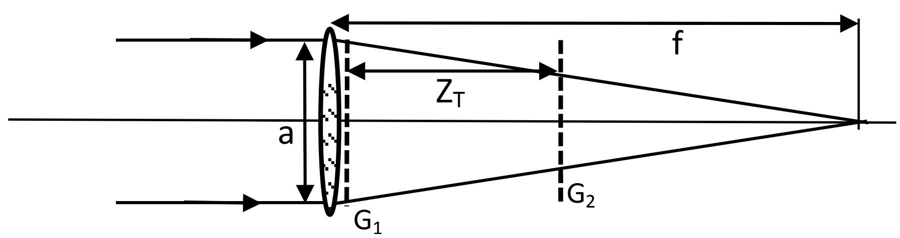

Fig 3. Measurement of long focal length using self-imaging and moiré phenomenon.

A modification of this method is as follows. The grating G_1 of period p with grating lines running parallel to y-axis is kept in contact with the test lens. A similar grating G_2 is placed at the nth Talbot plane making a small angle θ with the y-axis. The moiré fringe pattern makes an angle ϕ_n with the x-axis; the angle ϕ_n is measured and the focal length f is obtained from the formula

$$f = \frac{1}{\cos\theta + \tan\phi_n \sin\theta - 1}\frac{np^2}{\lambda}.$$

8 Multiplexing in speckle interferometry

Unlike holographic interferometry, experimental set up in speckle interferometry can be configured to measure only one of the components of the deformation vector. There are two distinct schemes to measure in-plane components. These are known as Leendertz method [13] and Duffy's method [14]. The out-of-plane component is measured using a Michelson interferometer in which one of the mirrors is replaced by the object under study.

The sensitivity of Leendertz method to measure in-plane components is higher than that of the Duffy's method. On the other hand, Duffy's method provides fringes of high contrast since the halos at the Fourier plane are isolated due to the carrier frequency in the speckle. It also provides the possibility of multiplexing. In the original configuration of Duffy's method, an opaque plate with two openings (apertures) on the center line is placed before the imaging lens: the images of the object formed via each aperture are identical and superimposed: the speckles in the image carry the fringes. When the images of the object with different loading conditions are recorded by varying the separation between the apertures, it is called frequency multiplexing. Instead of both the apertures being on the center line, one of the apertures can be placed anywhere before the imaging lens which results in theta modulation. In practice, we use several apertures and place optical components in front of some of the apertures in order to obtain in-plane displacement components, out-of-plane displacement component, slope patterns etc. for the same loading condition of the object [15-18].

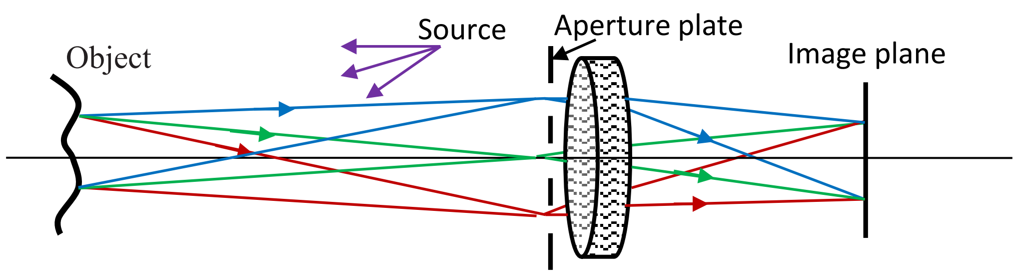

Fig 4. Experimental setup to measure in-plane component

Let us consider an experimental setup as shown in Fig 4, in which there are three openings (apertures) in the opaque plate placed before the imaging lens. The three apertures in the opaque plate are shown in Fig 5(a); the y-axis is vertical passing through the centers of the apertures.

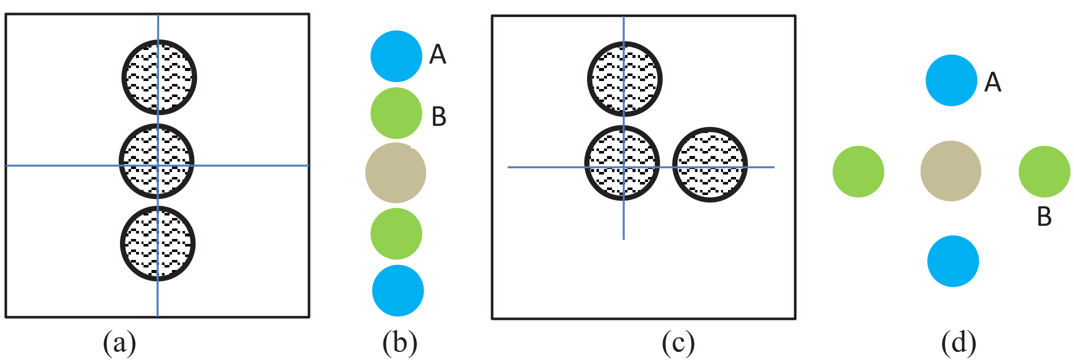

Fig 5. (a) Aperture configuration (b) Halo distribution (c) Aperture configuration (d) Halo distribution.

A double exposure specklegram, when illuminated with a collimated beam will produce a halo distribution as shown in the Fig 5(b). When imaging is done by filtering through halo B, a fringe pattern depicting fringes due to y-component of the in-plane displacement is formed. When imaging is done by filtering through halo A, a fringe pattern depicting fringes due to y-component of the in-plane displacement but double the sensitivity is formed. However, if the aperture configuration is altered to that shown in Fig 5(c), the halo distribution will be as shown in Fig 5(d). If the image is formed by filtering halo B, the fringe pattern will correspond to the x- component of the in-plane displacement. On the other hand, if the image is formed by filtering halo A, the fringe pattern will correspond to the y-component of the in-plane displacement. Aperture distribution can be further modified so that the fringe patterns corresponding to the out-of-plane component along with in-plane components are obtained by filtering appropriate halos.

Same concept is applied to speckle shear interferometry. In order to provide shear along x-and y-directions, wedge plates of a small wedge angle are placed on the apertures and properly aligned. In one experiment, the aperture plate carries four apertures as shown in the Fig 6. Two apertures carry the wedges W_1 and W_2 properly oriented. Aperture G carries a ground glass plate which is illuminated with an unexpanded laser beam to provide a diffuse reference beam. By imaging the object by filtering through appropriate halos, fringe patterns corresponding to x-slope, y-slope and out-of-plane displacement component can be retrieved from a single double exposure specklegram.

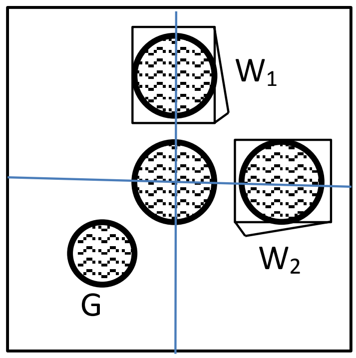

Fig 6. Aperture configuration in speckle shear interferometry.

Multi-aperture shearographic set up has been used to measure slope in orthogonal directions along with curvature and out-of-plane deformation. In fact, both electronic speckle pattern interferometry (ESPI) and shearography have been combined into one system [19]. Out-of-plane deformation fringes, slope fringes and curvature fringes can also be obtained from a three-aperture arrangement [20]. Also, the influence of in-plane displacement component on slope fringes has been examined [21].

Since a lens can be recorded holographically, both the functions of shearing and imaging have been combined into a single holographically recorded element which has been used in the shearographic set up [22]. This makes the shearography setup light weight as the holo-lens is a two-dimensional element.

Instead of a wedge plate, a holographic grating is used as a shear element, which is placed just in front of the image plane and full aperture of the imaging lens is used [23]. The grating produces three diffraction orders, 0 and ±1, orders. Hence three sheared images are formed. A doubly exposed shearogram when Fourier filtered generates 5 halos. Filtering one of the ±2 order halos gives slope fringes while filtering one of the ±1 order halos gives both the slope fringes and the curvature fringes as a result of moiré of the sheared slope fringe patterns.

Instead of obtaining slope fringe pattern after it has been deformed, slope contouring of the object can be performed by several methods: one of them is to change the refractive index of the medium surrounding the object in between the exposures. Radial and theta slope contours are obtained of some objects using this method. From slope contours, the shape of the object can be reconstructed. Various configurations for obtaining slope contours by the rotation of the object in between the exposures are summarized by Santhankrishnan *et al* [24,25].

Since in 1987, we also started using video camera for recording. Unlike photographic recording, the records (frames) can be independently handled in electronic recording. Hence, both additive and subtractive

ESPI with their attendant features can be performed. It was shown that the slope fringes can be sharpened using multiple frames [26]. Earlier, the sharpening of fringes was carried out either by using multiple exposures [27] or the non-linearity of the recording medium. Digital shearography is also used to measure the tilt of a planar object using inversion shear [28].

Digital shearography was used to test an object for its thickness uniformity [29]. The objective was to set a limit on the smallest thickness change that could be detected by the technique. Using two Michelson interferometers to provide shear, curvature fringes are obtained [30]. Several whole-field methods of non-destructive testing using electronic detection have been described [31]. Digital shearography is one of these techniques. Krishna Mohan *et al* have configured a TV shearography system by splitting the CCD in two halves to display out-of-plane deformation and its slope simultaneously in real-time [32]. Since multi-aperture configuration provides carrier frequency, it has been utilized for phase-shifting. Digital shearography with Fourier phase shifting has been implemented to obtain deformation, slope, and curvature maps.

Digital shearography is a mature, well-accepted technology used in non-destructive testing applications ranging across the marine, electronics, aerospace, automotive, tire and rubber industries. It has also found applications in artwork conservation. Shearography systems are both portable and fixed production applications.

9 Conclusion

This essay presents only a glimpse of the work done by our group in optical metrology. The contributions of the co-workers are gratefully acknowledged.

I had a good fortune to meet Prof Malacara during 19th International Symposium on Optomechatronics Technology (ISOT 2018) held in Cancùn, Mexico during November 5-8, 2018. I would like to thank Prof Amalia Martinez Garcia for inviting me to ISOT 2018.

Front row: Professor Daniel Malacara and Prof Rajpal Sirohi

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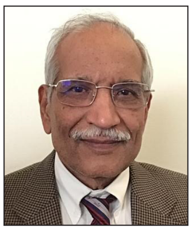

Having served as Professor of Physics at IIT Madras for more than two decades, Director of IIT Delhi and Vice Chancellor to several Universities in India, Distinguished Scholar to Rose-Hulman Institute of Technology, Terre Haute, USA, Chair Professor Tezpur University, Assam India, Faculty at Alabama A&M University, Huntsville, Alabama USA, Prof Rajpal Singh Sirohi is now retired. He spends his time in reading books on history of science and spends mornings and evenings with his grandchildren. He is the recipient of many (21) awards such as Vikram and Gabor awards from SPIE, Padmashri from Govt of India etc. He is the Fellow of two academies and many societies including SPIE, OSA, OSI etc. Prof. Sirohi's research areas are Optical Metrology, Optical Instrumentation, Laser Instrumentation, Holography and Speckle Phenomenon.