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TUTORIAL

Optical beam collimation procedures and collimation testing: a summary

Rajpal S. Sirohi*

Alabama A&M University, Department of Physics, Huntsville, Alabama, United States

Abstract. A collimated optical beam is required in several applications such as metrology, optical processing, free space propagation of information, and laser-based instrumentation. Prior to the advent of the laser, the size of the aperture at the focal point of a collimating lens determined the degree of collimation based purely on geometrical optics consideration. Because the laser beam can be focused to a tiny size, effectively making it a point source, the degree of collimation is governed by diffraction at the aperture of a collimating lens. A large number of procedures have been developed to collimate the beam. We examine the development of these techniques from the historical perspective. © *2020 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.59.4.040801]

Keywords: shear interferometry; Talbot interferometry; wedge plate; Lau effect.

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1 Introduction

A collimated optical beam is required in several applications, such as metrology, optical processing, free space propagation of information, and laser-based instrumentation. Errors in measurement can occur if the beam is not properly collimated. Due to its importance, this topic has been extensively researched. Many diverse methods and techniques have been explored. Some of these are simple and practical, while many of them are of academic interest. Main techniques for collimation testing are shear interferometry and Talbot interferometry. Classical interferometry along with a phase conjugated mirror or a bi-mirror has also been used for collimation testing. There are also some papers using techniques that do not fall into either in shear interferometry or Talbot interferometry. This paper attempts to describe these techniques.

2 What is Collimation?

If a point source is placed at the front focal point of a positive lens, the beam leaving the lens is a parallel beam under geometrical optics consideration. Note that a parallel beam is an academic idealization and does not exist in practice. The spherical wave from the point source is diffracted at the lens aperture, and the exiting beam is now called a collimated beam. This beam, if captured by another positive lens of a larger aperture, will not focus to a point but to a region with an irradiance distribution called an Airy pattern, which occurs due to diffraction at the first lens. By contrast, if the beam is captured by a lens of smaller aperture, the Airy pattern would be due to diffraction at the second lens. The central disc of this pattern contains about 85% of the energy of the beam, and its size is taken as an effective source size, which then defines the degree of collimation. The degree of collimation is half of the angle that the source subtends at the center of the collimating lens, which is given by $\alpha = 0.61\lambda/D$, where D is the diameter (aperture) of the lens. Obviously, this angle will be smaller for a larger aperture lens. Therefore, a point source can be replaced by a source of finite size.

When we wish to expand and collimate a laser beam from a laser oscillating in TEM_{00} mode, we assume that a planar wavefront of beam waist $2\omega_0$ lies at the front focal plane of the lens of

*Address all correspondence to Rajpal S. Sirohi, E-mail: rs_sirohi@yahoo.co.in

focal length f. The spot size $2\omega(f)$ at the lens aperture is $2\omega(f) = 2\omega_0[1 + (\frac{f}{z_0})^2]^{\frac{1}{2}}$, where $z_0 = \frac{\pi\omega_0^2}{\lambda}$ and λ is the wavelength of laser radiation. The beam waist $2\omega_c$ lies at a distance f from the lens; ω_c is nearly the same as $\omega(f)$. If the spot size $2\omega(f)$ is equal to the diameter D of the lens, 86.5% of the incident power is transmitted by the lens. The irradiance across the lens aperture is not uniform, being maximum at the optical axis and about 14% at the periphery of the lens aperture. If a more uniform beam is required, it is to be over-expanded at the expense of available power.

When a beam from an incoherent source is to be collimated, an aperture of diameter $2a$ is placed at the front focal point of the collimating lens of focal length f. The semidivergence angle θ of the beam is now given by $\theta = \tan^{-1} \frac{a}{f}$.

3 What is the Limit of Collimation?

For an incoherent source, the divergence is controlled both by the diameter of the aperture at the front focal point and the focal length of the collimating lens. A ratio in the range of 1/250 to 1/1000 is not uncommon and is decided by the available light throughput.

For coherent sources, diffraction limits the degree to which a beam can be collimated. The diffraction limited divergence is given by $\alpha = \frac{0.61\lambda}{D}$, where D is the diameter of the collimating lens. Obviously, a large aperture collimator provides a well collimated beam. For a collimating lens with an aperture of 10 cm, the diffraction limited divergence is on the order of 4 μrad when red radiation from a He–Ne laser is used.

4 Collimation Procedure

A point-like source is to be placed at the front focal point of the collimating lens to obtain a collimated beam. If it is not placed at this location, the beam may be either divergent or convergent, that is, it becomes a spherical wave. If Δf is the axial shift of the point-like source from the focal point, the radius of curvature R of the emergent beam is $R = \pm \frac{f^2}{\Delta f}$. If the axial shift is outward from the focal point, it is a convergent beam; if it is inward (toward the lens), it is a divergent beam. When $\Delta f = 0$, R becomes infinite and the beam is then collimated. Many methods of collimation testing rely on this characteristic, that is, they check whether the beam is spherical or not.

5 Method of Collimation Testing

The methods can be grouped under the following categories:

- classical methods
- shear interferometry
- interferometry
- Talbot interferometry (Talbot and moiré phenomena)
- Lau effect and Lau interferometry
- special methods

5.1 *Classical Methods*

For over a century, telescopes have been aligned and tested for their performance using the star test.[1] This is a visual but quite useful test. A telescope then can be used for setting up a collimator. The telescope receives the beam from the collimator, and the position of the pinhole (aperture) near the front focal point of the collimating lens is axially adjusted until its sharp image is seen in the telescope. The beam exiting the collimating lens is now collimated. It should be noted that this is the method used to set up a collimator for doing an experiment either with a prism or a grating on a spectrometer.

It is also possible to align the collimator by measuring the modulation transfer function (MTF) of the collimator. This is feasible because there are methods available that can be used to measure the MTF in almost real time.[2]

In another classical method of beam collimation, the beam from the collimating lens is retro-reflected and the location of the pinhole is axially adjusted until a sharp image of the pinhole is formed on itself.

However, the simplest method is to observe the size of the beam at several planes along its direction of propagation, and the position of the pinhole is adjusted until the sizes at several planes are nearly the same. The beam from a CO_2 laser was collimated by observing the shape and size of the beam taken on a thermal paper.[3] The knife edge method is also used to get the beam spot size at various locations along the direction of propagation. Many classical methods for obtaining collimated beam are discussed by Van Heel.[4]

5.2 *Shear Interferometry*

It is known that interference between two laterally shifted spherical waves produces a straight-line fringe pattern whereas interference between two laterally shifted plane waves produces a uniform illumination. With the advent of lasers, it became possible to observe interference patterns even when waves with large path difference were superposed. The first application of shear interferometry for collimation testing using a plane parallel plate (PPP) for shearing was reported by Murty.[5] Subsequently, a wedge plate and several of its variants were used for collimation testing.[6–8]

5.2.1 *Plane parallel plate shear interferometer*

The beam from the collimating lens is incident on a PPP that is placed inclined to the beam. The beams reflected from the front and back surfaces of the plate are laterally sheared, and the interference is observed in the overlap region. The magnitude of shear depends on the angle of incidence, and for smaller angles shear is linearly related to the angle of incidence. When the point source is axially shifted by Δf from the focal point, the beam from the collimating lens can be described by a path function $W(x, y)$, which is given by

$$W(x, y) = \frac{x^2 + y^2}{2R},$$

where x and y are Cartesian coordinates on a plane perpendicular to the optical axis and R is the radius of curvature of the beam. Taking this as the path function of the beam reflected from the front surface of the PPP, the path function for the beam reflected from the back surface can be described by the path function $W(x - \Delta x, y)$, which is given by

$$W(x - \Delta x, y) = \frac{(x - \Delta x)^2 + y^2}{2R'},$$

where Δx is the shear, assumed to be along the x direction, and R' is the radius of curvature, being different from R due to additional travel distance through the glass plate. Ignoring the phase change on reflection at the front surface, the condition for bright fringes in the interference pattern can be expressed as

$$W(x, y) - W(x - \Delta x, y) = \frac{x^2 + y^2}{2}\frac{\Delta R}{R^2} + \frac{x\Delta x}{R} = m\lambda,$$

where m is the fringe order, λ is the wavelength, and $\Delta R = R' - R$. Further, the term containing $(\Delta x)^2$ is dropped. When near collimation condition, $\Delta f \ll f$ and hence $R' \sim R$, the quadratic term can also be dropped. The interference pattern contains straight-line fringes: the fringe width $\bar{x}$ is given by

$$\bar{x} = \frac{\lambda R}{\Delta x} = \frac{\lambda f^2}{\Delta x \Delta f}.$$

The fringe width becomes infinite when $\Delta f = 0$, that is, when the point source is right at the focal point. On either side of this position, straight line fringes running parallel to the y axis are formed.

A shear interferometer with a large shear was realized by Shukla et al.[9] by utilizing two plates whose separation could be varied to change the amount of shear. They claim this to be more sensitive for collimation testing. When the collimation of a narrow beam is to be tested, a PPP does not serve the purpose as the two beams from the front and back surfaces do not overlap. A shear plate with a small shear can be realized either using two plates placed parallel but close to each other or placing the diagonal surfaces of two right angle prisms (double prism) parallel to each other but with a small gap.[10]

Wang et al.[11] used a PPP as a shear plate for collimating the beam from a laser diode. First, the beam was corrected using a combination of aspheric lens and cylindrical lenses and then collimated by obtaining a fringe-free field.

Instead of using a shear plate, the beam is sheared with a pair of sandwiches of holo-lenses.[12] The holo-lenses are recorded with a collimated beam as a reference wave. This experimental arrangement is long and cumbersome. Rajkumar et al.[13] used holo-elements in close proximity. The holo-elements are recorded by interference between two collimated beams and hence are essentially sinusoidal gratings.

Another modification of the conventional shear plate interferometer is the quadruple-pass lateral shear interferometer in which a double prism, which acts as a shear device, is used as a beam splitter in a Michelson type interferometer and half of the beam is reflected back.[14]

It has been pointed out that the PPP shear interferometer has its limitations when used for testing collimation because we cannot distinguish between a fringe of infinite width and a fringe of width equal to the aperture of the PPP. Further, large diameter beams cannot be tested for collimation because PPP samples only a portion of the beam. It is suggested that a shear interferometer with a tilt orthogonal to the shear direction would produce straight line fringes when the beam is collimated, and the fringes would rotate when the beam departs from collimation.[15] It is much easier to detect a change in the direction of fringes than to identify the total absence of fringes. Therefore, it is better to use a wedge plate than a PPP as a shear device.

5.2.2 *Single wedge plate shear interferometer*

A wedge plate shear interferometer uses a wedge plate of a very small wedge angle α ($\alpha \sim 10$ arc sec.). When placed normal to the beam, the beams reflected from the front and back surfaces are angularly sheared and there is a variable path difference between the two beams. When the incident beam is collimated, a straight-line fringe pattern with fringes running parallel to the edge of the wedge results. When this wedge plate is placed inclined to the beam, the reflected beams are laterally shifted, resulting in rotation of the fringes. The direction of rotation depends on whether the beam is convergent or divergent. Obviously, this is more sensitive than the PPP shear interferometer. Mathematically, we can describe the fringe formation by

$$\frac{x \Delta x}{R} + 2n\alpha y = m\lambda.$$

It is assumed that the wedge edge is parallel to the x direction. Here n is the refractive index of the material of the wedge plate and Δx is the amount of shear along the x direction. This equation represents a family of straight lines that make an angle θ with the x axis where $\theta = \tan^{-1}(-\Delta x / 2n\alpha R)$. When the beam is collimated, i.e., R is infinite, $\theta = 0$ and the fringes run parallel to the x axis. For finite R, these fringes are inclined.

Interestingly, the wedge plate can also be used in another orientation—the wedge edge is perpendicular to the lateral shear direction. In this situation, the condition for fringe formation is

$$\frac{x\Delta x}{R} + 2n\alpha x = m\lambda.$$

This gives a family of straight-line fringes running parallel to the y direction. The fringe width $\bar{x}$ is given as

$$\bar{x} = \lambda / \left(2n\alpha + \frac{\Delta x}{R} \right).$$

When the beam is collimated, the fringe width is $\bar{x} = \lambda/2n\alpha$. For a beam departing from collimation, the fringe width will be either more or less than that for a collimated beam. This configuration is generally not used as it is not as sensitive as the one that detects the change in inclination of the fringes. Riley and Gusinow[6] presented the theory of wedge plate shear interferometer and demonstrated its application for collimation testing. Later, Grindel[7] applied wedge plate shear interferometry for both collimation testing and for measuring the radius of curvature of a concave mirror. Dhanotia and Prakash,[16] instead of obtaining a collimated beam by visually observing the fringe pattern obtained with wedge plate shear interferometry, used the Fourier fringe analysis technique to calculate the phase of the wavefront, thereby achieving a much better setting accuracy.

For checking collimation of beams with diameters much larger than the diameter of the wedge plate, the beam is sampled at several locations. If a single wedge plate is used to check the collimation of beams of various sizes up to wedge plate diameter, it is designed so that the number of fringes observed with the smallest beam size is about two. This may ensure the same sensitivity for other beam sizes.

It may be noted that the angle of rotation of the fringe from the reference direction is directly proportional to the shear and inversely proportional to the angle of the wedge. Therefore, Shukla et al.[17] suggested a set of wedge plates with different angles and nominal thicknesses for use at certain ranges of angle of incidence to achieve optimum sensitivity for beams of diameters ranging from 3 to 100 mm. Udupa et al.[18] gave the design of a shear plate to be used with an unexpanded laser beam. It can be used both for collimation testing and to measure the radius of curvature of the beam.

5.2.3 *Wedge plate multiple beam shear interferometer*

Multiple reflections produce narrower (sharper) fringes. Sirohi et al.[19] used a coated wedge plate in transmission for collimation testing and for some other applications such as lens testing. Senthilkumaran et al.[20] used a coated wedge plate both in transmission and in reflection for collimation testing and showed that the reflection mode provides better setting accuracy. Matsuda et al. designed a wedge plate such that there is only one fringe running parallel to the base when the beam is collimated.[21] Such a plate can be used to check collimation of any size beam. Further, it is much easier to sense the inclination of the narrow fringe; therefore, a coated wedge plate shear interferometer has better sensitivity compared with its uncoated counterpart. It has also been shown that it could be used to collimate a beam even when the collimating lens suffers from aberrations.[22]

5.2.4 *Double wedge plate shear interferometer*

The wedge plate shear interferometer is quite sensitive, but it requires a reference line—a fiduciary line—to which the fringes are parallel when the beam is collimated. Sirohi and Kothiyal proposed a double wedge plate shear interferometer using two identical wedges with their apex opposite to each other and wedge edges parallel to each other.[8] Equations for fringe formation in both wedge plates are

$$\frac{x\Delta x}{R} + 2n\alpha y = m\lambda,$$

$$\frac{x\Delta x}{R} - 2n\alpha y = m'\lambda.$$

These represent a family of straight-line fringes making an angle of $-\theta$ and θ, respectively, with the x axis. For a collimated beam, the fringes run parallel to each other in both wedge plates. This, therefore, is a self-referencing method requiring no reference line or fiduciary line and also offers double the sensitivity.

If this pair of wedge plates is rotated by 90 deg in their plane, it converts to an interferometer in which the widths of the fringes are the same in both wedge plates when the beam is collimated. Otherwise, the fringe widths are different in both wedge plates.[8,23,24] Vernier acuity now plays a part in ascertaining the collimation. Unlike a single wedge plate shear interferometer, the double wedge plate shear interferometer can be used, in fringe mode, for collimation testing with good setting accuracy.

Several modifications/new configurations of double wedge plate shear interferometer have been proposed and demonstrated.[25,26]

It is obvious that both of these techniques require a composite wedge plate in which two identical wedge plates are aligned antiparallel. To avoid this cumbersome alignment, a single wedge plate is fixed on a mount that could be rotated exactly by 180 deg to obtain the second interferogram.[27–29] Essentially, the technique provides double the sensitivity and possesses self-referencing. Zhang et al. used a wedge plate in which the resulting interference pattern appearing on a ground glass plate is grabbed and stored. The wedge plate is rotated by 180 deg, and the interference pattern is again grabbed. These two patterns are digitally subtracted to obtain the moiré fringe pattern.[30] At collimation, a fringe-free field is obtained; otherwise, straight-line moiré fringes are observed. Li et al.[31] proposed a method to obtain two sets of interference fringes from a single wedge plate. The wedge plate acts as a beam splitter in a Michelson interferometer. The mirrors are tilted such that two sets of interference fringes appear side by side. This technique was devised to overcome the problem of aligning two wedge plates[8,23] or the requirement for an accurate rotator.[27–29] However, obtaining these two sets of fringes side by side is not easy. This problem was, however, eliminated by Lee et al. by masking the lower half of one mirror and the upper half of the other mirror of a Michelson interferometer.[32] The two patterns thus formed are one above the other. This arrangement has been demonstrated for both configurations: rotation of fringes and change of fringe width. It is shown that both configurations provide the same degree of collimation. In another method, a right-angle prism in retroreflector mode is used.[33] Half of the diagonal surface of the prism is coated. Two sets of fringes, one on the reflection from the mirrored surface and the other on the retroreflection from the other half-surface, are formed when the wedge plate is used as a beam splitter. An interesting arrangement to generate two fringe patterns from a single wedge plate uses a combination of a wedge plate and a diagonal coated cube.[34] This reversal interferometer has been demonstrated in two different configurations. It is interesting to note that two US patents were granted on the techniques outlined above.[35,36]

5.2.5 *Hybrid techniques*

These techniques use both a wedge plate and a grating. Darlin et al.[37] used a single wedge plate along with a composite grating to produce a moiré pattern. This hybrid arrangement provides double the sensitivity due to the composite grating. The techniques described so far use wedge plates of very small angles (∼10 arc sec.), resulting in a few fringes in the field of view for visual observation. By contrast, one can also use a wedge plate with a large angle (∼80 arc sec.) such that the fringes formed when the beam is collimated have a higher spatial frequency (∼2.5 lines per mm). A pair of such wedge plates of slightly different wedge angles is placed in the beam at two locations.[38] These are adjusted to produce identical fringe patterns, which on superposition produce a moiré pattern. This moiré pattern is used for collimation testing. Disawal et al.[39] used a single wedge plate of about 50 arc sec wedge angle and a linear grating to produce a moiré pattern and calculated the phase of moiré fringes using a temporal phase-shifting technique. At collimation, the phase is constant across all pixels along the shear direction.

A Fresnel bi-prism, usually used for conducting interference experiments, would be an ideal element when used in reflection along with a composite grating for collimation testing using moiré fringes.

5.3 *Interferometry*

Langenbeck proposed an improved collimation technique in which one of the mirrors of a Michelson interferometer is replaced by a pair of corner cube reflectors (CCRs), making it an inverting interferometer.[40] Displacing the CCRs perpendicular to the optical axis introduces shear. The orientation and spacing of the fringes are controlled by the plane mirror. On collimation, the fringes will be parallel in both retroreflected beams, whereas they will be oppositely rotated when the beam departs from collimation. Langenbeck even proposed a compact arrangement consisting of several small CCRs on a glass plate that has a transmissive reference coating: interference between the beam reflected from the reference coating and retroreflected beams from the CCRs generate several interference patterns. Fringes in all CCR patterns will be parallel to each other for a collimated beam.

If the path difference between the two arms of a Michelson interferometer is very large, the fringes in the interference pattern will be circular when the incident beam is a spherical wave. A fringe-free field is obtained only for a collimated beam.[41]

If one of the mirrors of a Michelson interferometer is replaced by a phase-conjugate mirror, then one observes interference between the convergent and divergent beams when the beam is not collimated, giving curved fringes whose curvature changes on either side of the collimation condition.[42,43] A straight-line fringe pattern is obtained only when the beam is collimated. Darlin et al. increased the sensitivity of this technique using a bi-mirror along with a phase conjugated mirror.[44]

A Michelson interferometer can also be adapted for shear interferometry. One of the mirrors of the interferometer is replaced by a right-angle prism, which folds the incident wavefront. Shear is introduced by the shift of the prism in its plane. The right-angle prism can be replaced by a pair of mirrors enclosing an angle of $(90\ \deg - \alpha) : \alpha$ being very small. This provides self-referencing and doubles the sensitivity. Such an interferometer can also be used to check collimation of nonvisible beams provided the beam splitter is appropriately chosen. Chen et al.[45] used such an interferometer to test the collimation of a beam from a CO_2 laser.

Henning and Carlsten[46] proposed a cyclic interferometer, in which shear is introduced by the shift of one of the mirrors, for measuring the radius of curvature of a short-coherence length laser beam and collimating the beam. By replacing a mirror of the cyclic shear interferometer by a bi-mirror, self-referencing can be built.[47] This self-referencing cyclic shear interferometer is demonstrated for both fringe rotation and fringe width mismatch modes of operation.

5.4 *Talbot Interferometry*

A grating illuminated with a plane wave self-images itself periodically. The separation between the self-images is $z_T = 2a^2/\lambda$, where a is the period of the grating and λ is the wavelength. The distance z_T is known as Talbot distance. When the grating is illuminated by a spherical wave, the self-images are not equally spaced, and the period of the self-image is different than that of the grating. Talbot phenomenon, when used in conjunction with moiré phenomenon, yields a technique known as Talbot interferometry. When two linear gratings with the grating vectors making an angle of $+\theta$ and $-\theta$ with the x axis are in close proximity to each other, a moiré pattern with fringes running along x axis is formed: the fringe spacing is $\bar{y} = a/2 \sin \theta$. If the period of one of the gratings changes, the moiré fringes rotates, i.e., they make an angle with the x axis. When the two gratings are identical and aligned such that their grating elements are parallel to each other, the moiré pattern will be of uniform illumination (infinite fringe mode). Gratings with slightly different periods but with grating elements parallel to each other and along the x axis produce a moiré pattern in which the period of moiré fringes is $\bar{y} = ab/|a - b|$, where a and b are the periods of the gratings. The moiré fringes are parallel to the x axis.

Silva[48] demonstrated that Talbot interferometry is a good technique for collimation testing. He used two identical gratings: self-image of the first grating falls on the second grating, which is aligned in an infinite fringe mode. In this mode, the fringe width is directly proportional to the radius of curvature of the wave that illuminates the first grating. He also showed that the moiré fringes are formed when the second grating is rotated in its plane such that grating elements in the self-image of the first grating make an angle with the elements of the second grating. The moiré fringes rotate if the first grating is illuminated by a spherical wave. On collimation, the moiré fringes are parallel to a reference direction.

Several other researchers demonstrated the application of Talbot interferometry for collimation testing.[49–52] Instead of using two gratings, a single grating with its self-image formed by reflection from a plane mirror on itself has been used for collimation testing.[49] The arrangement is relatively compact, but departure from collimation is detected by the change in fringe width. A modification of this uses a right-angle prism (porro prism) instead of a plane mirror for folding the path so that the self-image of the grating is formed on itself.[53] The porro prism is placed such that its edge is vertical and the grating elements make a small angle θ with the horizontal. Due to retroreflection, the grating image is folded about the vertical; thus, its elements make an angle $-\theta$ with the horizontal. The position of a porro prism is adjusted so that the retroreflected self-image falls on the grating, thereby forming a moiré pattern in which the fringes run parallel to the edge of the prism for a collimated beam. If the incident beam is spherical, the moiré fringes rotate. The method is self-referencing and easy to perform.

Talbot interferometry has also been performed using a single grating, which is kept in the beam, and a CCD is located at the Talbot plane.[54,55] The self-image captured is subtracted from a previously stored image of the grating. Departure from collimation produces a self-image with a slightly different period, which on subtraction, produces moiré fringes. The correct position of the point source is determined by observing identical moiré fringes on either side of the collimation condition.[55] It is known that divergence or convergence can be altered by changing the beam size. This idea is utilized by inserting a two-lens system after the collimating lens to increase the divergence/convergence and then using Talbot interferometry for collimation testing.[56,57] Apart from a linear grating, other grating types such as circular gratings,[58] spiral gratings,[59–61] spiral gratings with wavelet transform,[62] arc gratings,[63] triangular gratings,[64] and evolute gratings[60] have been employed for collimation testing by many researchers. In another arrangement, instead of two identical gratings, a linear grating and a differential grating (composite grating containing linear gratings of different periods in each half) are used: the differential grating is placed at the Talbot plane of the linear grating.[65] At collimation, both halves have the same pattern, whereas with a noncollimated beam, the fringes in the two halves have different widths. Instead of keeping both of the gratings stationary and observing the moiré fringes, the first grating is translated with a constant velocity in the direction of the grating vector and the phase of the heterodyne moiré signal is calculated.[66] At collimation, the phase slope is zero.

Because the phase of the moiré fringes varies linearly when the beam departs from collimation, several methods that determine the phase when the point source is translated through from an out-of-focus position to an in-focus position by small amount have been investigated. Methods used for determining the phase information include the phase-shifting method,[67] Fourier transform,[68] and windowed Fourier transform.[69] Patorski et al.[70] used circular and linear gratings along with wavelet transform to determine the phase in the moiré pattern. Sanchez-Brea et al.[71] proposed a two-grating arrangement in which the second grating has two-halves shifted by a quarter of the period. A pair of photodetectors is placed behind each half. When the first grating is translated with a uniform velocity, the phase difference between the heterodyne moiré signals depends on the degree of collimation of the beam. These signals can also generate Lissajous figures; the ellipticity of the figure depends on the degree of collimation. When the beam is collimated, the Lissajous figure is a circle. In a modification to this technique, the second grating consists of a mask of many Ronchi gratings appropriately shifted. Signals from photodetectors behind each Ronchi grating in the mask are used to generate Lissajous figures without the translation of the first grating.[72] It may be remarked that phase estimation techniques are accurate, precise, automated, and relatively easy to implement.

Recently, collimation testing based on determining the period of self-images using a variogram function has also been reported.[73–75] The technique uses a single grating. In one technique, the period of self-image of the grating is compared with the period of the grating.[73] In a variation of this technique, the periods of the self-images at two different Talbot planes are compared.[74] The periods of the grating and its self-images are the same when the grating is illuminated by a collimated beam. With spherical beam illumination, the periods are different. This technique is also applied to collimate a beam from a white LED.[75]

In a recent work, Rana et al.[76] captured the self-images of a grating at the first and second Talbot planes and computed the statistical correlation coefficient. Correlation coefficient estimates the similarities between the two images; the value is 1 if the images are absolutely identical and 0 if they are uncorrelated. When the point source is at the focal point, the correlation coefficient is nearly one; otherwise, its value is less than one.

5.4.1 *Composite grating*

A composite grating consists of two identical gratings that either enclose an acute angle or an obtuse angle. A pair of such gratings is used in Talbot interferometry for collimation testing.[23,60,77,78] This approach provides self-referencing and doubles the sensitivity. Another variant of the composite grating consists of two gratings of slightly different periods.[26,65] A pair of these can be used in Talbot interferometry. At collimation, the fringe width in both halves is the same. For a convergent beam, the fringe width in one half is greater than in the other half. This changes when the beam is divergent, thereby providing self-referencing.

5.5 *Lau Effect*

The Lau effect is an interference phenomenon involving a pair of coarse gratings in tandem with the grating elements parallel to each other and back illuminated by a polychromatic extended source. Colored fringes are observed at infinity for all separations of the gratings. High-contrast fringes are observed for distances $na^2/2\lambda$ between the gratings when they are illuminated by narrowband light, where n is an integer, a is the grating period, and λ is the mean wavelength.

Avudainayagam and Chitralekha[79] observed that Lau fringes, for small grating separations, rotate when the first grating is illuminated by a nearly collimated beam and the second grating is rotated in its own plane. The fringes rotate in the same direction as the second grating when the illumination is by a diverging wave and in the opposite direction when it is by a converging wave. When the first grating is illuminated with a collimated beam, the Lau fringes stagger and then vanish.

Instead of the two gratings being separated by a finite distance, Patorski[80] suggested an arrangement in which the separation between the two gratings is infinite. This is achieved by placing the first grating illuminated by an incoherent source at the front focal plane of a lens and the second grating after the lens. In such an arrangement, second grating self-images at certain planes where a third grating is placed to observe moiré fringes, essentially making this equivalent to Lau interferometry. Such an arrangement with three gratings with elements aligned parallel to each other has been used by several researchers for collimation testing.[81–84] At collimation, a fringe-free field is obtained, whereas there are straight-line fringes if the beam is not collimated. In another variant, the second and third gratings are rotated in their plane oppositely by a very small amount resulting in the formation of fringes. The fringes run parallel to the x axis when the beam is collimated and rotate in opposite directions when the beam is convergent or divergent.[82,83] The phase of these fringes is measured to automate the system using the phase-shifting technique[84] and the Fourier fringe analysis technique.[85]

5.6 *Special Techniques*

Bass and Whittier[86] used a small corner-cube retroreflector that is translated a small distance perpendicular to the beam axis and measured the translation of the retroreflected beam. If the displacement of the retroreflected beam is equal to the displacement of the corner-cube retroreflector, the beam is collimated. This method of collimation is based purely on geometrical optics.

Prasad et al.[87] wrote a 4×4 lenslet array on LCTV and used it for collimating a beam by finding the centroids of the point spread functions of the lenslet array.

In the method proposed by Senthilkumaran,[88] the test beam is an input beam to a Michelson interferometer with a large path difference. A spiral phase plate is introduced in one of the arms (longer arm) of the interferometer, and the interference pattern is observed. On collimation, radial fringes are observed; otherwise, the fringe shape is spiral.

Anand and Narayanamurthy[89] recorded an interference pattern on a bismuth silicone oxide ($Bi_{12}SiO_{20}$) crystal. The path difference between the recoding beams is large but within the coherence length. It is shown that the diffraction efficiency is maximum when the recording

Table 1 Reported setting accuracies for various collimation methods.

Technique		f (mm)	Aperture (mm)	Δf (μm)	$(\frac{\Delta f}{f})$ %	Reference # (year)
Shear	Quadruple pass	100	25	3	0.003	14 (2014)
	Wedge-Fourier fringe analysis	250	50	1	0.0004	16 (2011)
	Hybrid	250	50	~20	0.008	37 (1998)
	Shear interferometry-CO_2 laser wavelength	254	50	250	0.098	45 (1996)
	Parallel plate	100	100	3.4	0.0034	38 (1995)
	Wedge plate	100	100	0.34	0.0003	38 (1995)
	Multiple beam	250	50	30	0.012	20 (1995)
	Double wedge	250	50	51	0.0204	26 (1993)
	Wedge rotation	400		36	0.009	27 (1991)
	Parallel plate	60	10	7.5	0.0125	40 (1970)
Talbot interferometry	Digital correlation	200		13	0.0065	76 (2018)
	Dual camera	40	17	0.3	0.0007	74 (2016)
	Heterodyne moiré	100		7	0.007	66 (2014)
	CMOS camera	25	20	0.6	0.0025	73 (2014)
	Differential grating	50	12.5	0.1	0.0002	65 (2014)
	Hybrid-phase shifting	250		11	0.0044	39 (2013)
	FT method	250		24	0.0096	68 (2011)
	Lissajous figures-two cameras	9		0.5	0.0056	71 (2010)
	Circular grating-seventh Talbot plane	300		29	0.0097	58 (2001)
	Triangular grating	200		40	0.02	64 (1997)
	Composite	250	50	62	0.0248	26 (1993)
	Ronchi	500	40	200	0.04	52 (1976)
		200	50	10	0.005	48 (1971)
Lau interferometry		250	50	30-visual 1-Fourier fringe analysis	0.012 0.0004	85 (2014)
Special methods	Dammann grating	250	20	50	0.02	92 (2007)
	Optically active material	200	10	20	0.01	90 (2005)
Interferometry	Phase conjugation	250	50	20	0.008	44 (1998)
	Cyclic	250	50	40	0.016	47 (1997)

beams are collimated. Later, Anand et al.[90] also showed that the irradiance of the beam passing through a birefringent material (quartz) placed between crossed polarizers varies with departure from collimation: it is minimum when the beam is collimated.

In a method proposed by Zhang et al.,[91] a small circular aperture samples a beam that needs to be collimated. The aperture is placed abutting a high-quality collecting lens. Behind this lens, two planes that display identical diffraction patterns of the aperture are found. The separation between these planes is related to the wavefront error of the beam.

Zhao and Chung[92] used a one-order binary phase circular Dammann grating for collimation testing. The grating generates two uniform-intensity impulse rings in the far field. The separation of the rings is minimum when the beam is collimated.

The Fresnel diffraction pattern of a slit imaged on a CMOS sensor has been used to collimate a beam.[93] It is shown that the separation between the primary peak point and the secondary peak point in the diffraction pattern is related to the defocusing.

6 Conclusion

A large number of techniques and methods to collimate a beam originating either from an incoherent or a coherent source have been investigated and demonstrated. These exhibit a range of setting accuracies. Table 1 is a compilation of data from various publications. Though there are a large number of techniques that have been mentioned in this paper, two of them, namely shear interferometry and Talbot interferometry, have been researched and used the most for collimation testing. Wedge plate shear interferometry provides better sensitivity as compared with PPP shear interferometry. It is also to be noted that the setting sensitivity in shear interferometry depends on (i) the angle of the wedge, (ii) $F\#$ of the collimating lens, and (iii) magnitude of the shear. Shear interferometry can be performed in a relatively small space. The setting sensitivity in Talbot interferometry depends on (i) the frequency of the grating, (ii) number of the Talbot plane, and (iii) $F\#$ of the lens. Talbot interferometry requires a relatively large space to perform. However, if a grating of very small period is used at its first Talbot plane, the space requirement is considerably reduced.

It may also be noticed that when fringe processing techniques are used in both of these techniques, the setting accuracy is considerably improved. This, however, requires additional hardware such as CCD camera(s) and fringe processing software.

The use of spiral and evolute gratings in Talbot interferometry does not yield good sensitivity. The Dammann grating appears to be promising, but its cost may be prohibitive to be routinely used for collimation testing.

A technique for routine collimation testing should be simple, requiring a minimum of components, and should have good setting accuracy. It is suggested that a pair of well-designed wedge plates properly aligned or a pair of composite gratings enclosing an acute angle would be a good choice.

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Rajpal S. Sirohi is a fellow of the Indian National Academy of Engineering, National Academy of Sciences, Optical Society of America, Optical Society of India, SPIE, and Instrument Society of India and is an honorary fellow of Indian Society for Technical Education and Metrology Society of India. He is a senior editor for *Optical Engineering*. He has published 248 papers in archival journals and written several books. He is the recipient of many awards, notable are the Gabor and Vikram awards from SPIE and Padmashri from the Government of India.