Development of a Shearing Interferometer for Testing Optical Communications Terminals

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Motivation

- Payloads that use refractive optics (lenses) will have a different focal length in vacuum.
- During the development and testing of experimental payloads, we want to offset the collimation of a beam to simulate vacuum without using a vacuum chamber.
- We need a device to measure the collimation of the adjusted beam: **a shearing interferometer**.

Shearing Interferometers

- Shearing interferometers are used to determine if a coherent beam of light is collimated, and to what degree.
- How it works (refer to Fig. 1):
  1. A coherent beam is directed toward a wedged optical flat.
  2. Part of the beam is reflected off the front surface; another part of the beam refracts into the wedge and then reflects internally; a last part of the beam refracts into and out of the wedge.
  3. Two parts of the beam interfere, producing fringes.
  4. The deviation angle of the fringes from the reference determine the degree of collimation (when the wavefront is not well-collimated it will have a radius of curvature R).

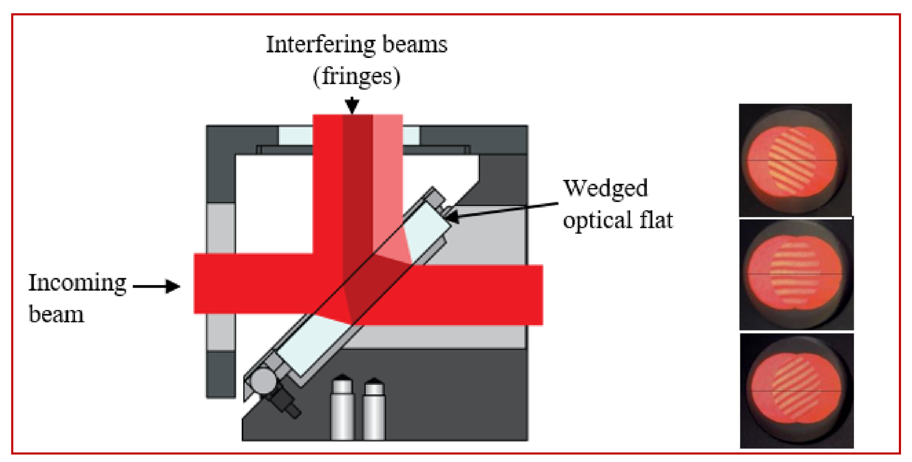


Fig. 1 – Shearing interferometer schematic.
Path of light through the shearing interferometer (left) and fringe patterns for collimated, diverging, and converging beams (right). Sourced from [3].

- The angle of deviation of the fringes from the horizontal ξ is given by [1]

$$\sin\xi = \frac{sd}{\lambda R},$$

where the fringe spacing d is dependent on the wavelength of the light λ, index of refraction of the wedge plate n, the wedge angle α, and the angle of incidence of the incoming beam onto the wedge plate i, [1]

$$d = \frac{\lambda}{2\alpha\sqrt{n^2 - sin^2 i}},$$

and s is the shear, a measure of the separation between the two reflected beams, calculated from the angle of incidence and the thickness t and index of refraction of the wedge, [2]

$$s = \frac{t\, sin(2i)}{\sqrt{n^2 - sin^2 i}}.$$

- As a result, the radius of curvature is related to the fringe deviation angle by

$$R = \frac{t\, sin(2i)}{2\alpha\, sin\, \xi (n^2 - sin^2 i)}$$

with propagated error

$$dR = |R| \sqrt{\frac{dt^2}{t^2} + 4\left[\frac{1}{tan(2i)} + \frac{\alpha R\, sin\, \xi}{t}\right]^2 di^2 + \frac{d\alpha^2}{\alpha^2} + \frac{d\xi^2}{tan^2 \xi} + \frac{4n^2}{(n^2 - sin^2 i)^2} dn^2}$$

Experimental Setup

The laboratory set-up for this technology demonstration consisted of a few key pieces of optical equipment: a coherent light source, optical fibers, collimator, camera and lens, and wedged optical flat.

A 780 nm polarization-maintaining fiber-coupled laser source was used with polarization-maintaining optical fibers and a fiber-optic collimator to guide and form the light into a free-space collimated beam. The wedged optical plate was Edmonds Optics Ø3" λ/10 Fused Silica Dual Surface Flat 43-428 with a wedge angle ≤ 1'. A monochromatic FLIR Blackfly S BFS-U3-200S6M camera was used to capture images of the fringe pattern caused by the refractions from the wedge plate. The CCD consists of 5472 pixels x 3648 pixels, where the pixel size is 2.4 µm. A Navitar DO-5095 High Speed 50 mm F0.95 TV Lens was used to focus the reflected beams onto the camera CCD during alignment.

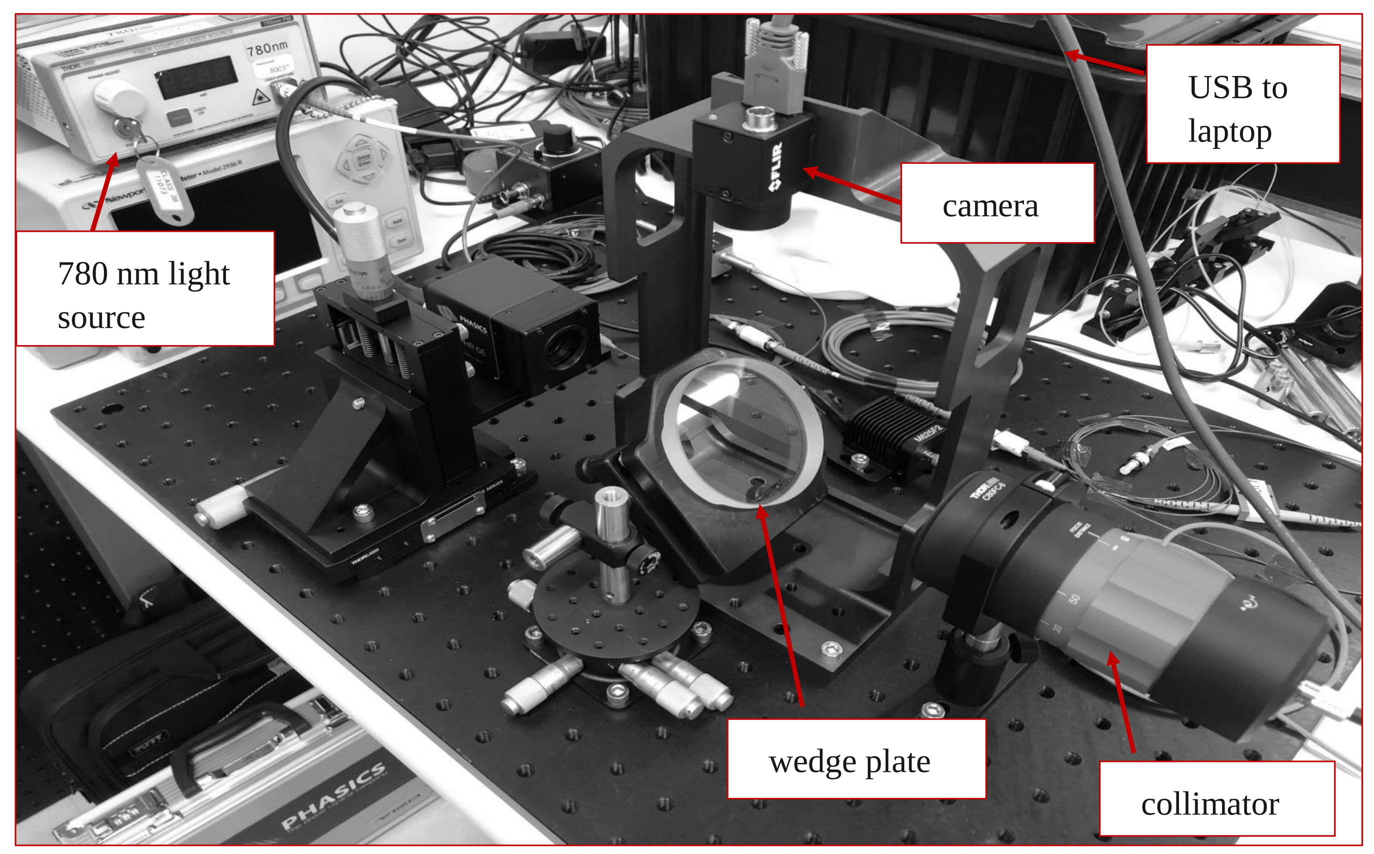


Fig. 2 – Shearing interferometer set-up in the laboratory.

Error Budget

The accuracy of the measurement of the radius of curvature is dependent on:

- Our knowledge of the thickness of the wedge plate, i.e. dt.
- Our knowledge of the index of refraction of the wedge plate, i.e. dn.
- Our knowledge of the incidence angle between the incoming beam and the wedge plate, i.e. di.
- Our knowledge of the plate's wedge angle, i.e. $d\alpha$.
- Our knowledge of the intrinsic angle between the wedge plate and the camera pixels *and* the measurement of the fringe deviation angle with respect to this reference, i.e. $d\xi$.

How does each parameter contribute to the error dR?

Consider, for example, making a measurement of a beam with a radius of curvature of $R = 10000$ m with the parameters as listed below. The error contribution for each parameter is shown in Fig. 3.

- $n = 1.45 \pm 0.01$
- $\alpha = 25 \pm 3$ arcsec
- $t = 15 \pm 1$ mm
- $i = 45 \pm 5°$
- $\xi = 0.221 \pm 0.05°$

The total error dR is 2709 m.

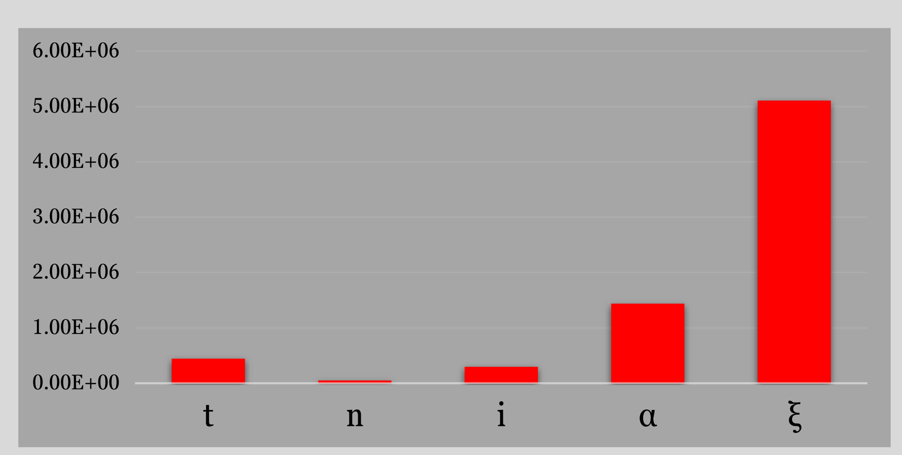


Fig. 3 – Contributions of parameter errors.
The terms under the square root in the calculation of dR.

Measuring the Fringe Deviation Angle

From the error budget, the uncertainty in the fringe deviation angle contributes most to the error in the radius of curvature. An extensive study was undertaken to compare different methods of determining the fringe deviation angle. The most successful method in achieving this measurement was the **"Linear Fit" method**, shown in Fig. 4, and is done as follows:

1. Co-add data images together to obtain higher signal-to-noise ratio, Fig. 4(a).
2. Apply FFT to the image data, Fig. 4(b).
3. Cut-off high frequencies to apply iFFT and obtain a filtered image, Fig. 4(c).
4. Extract fringe centers, Figs. 4(d) and (e), using a Gaussian best fit with a general form

$$f(x) = A_1 e^{-\frac{1}{2}\left(\frac{x - x_{0,1}}{\sigma_1}\right)^2} + A_2 e^{-\frac{1}{2}\left(\frac{x - x_{0,2}}{\sigma_2}\right)^2} + B$$

4. Fit the extracted centers with a straight line, Fig. 4(f).
5. Calculate the fringe deviation angle from the slope, $\xi = tan^{-1}(|m|)$

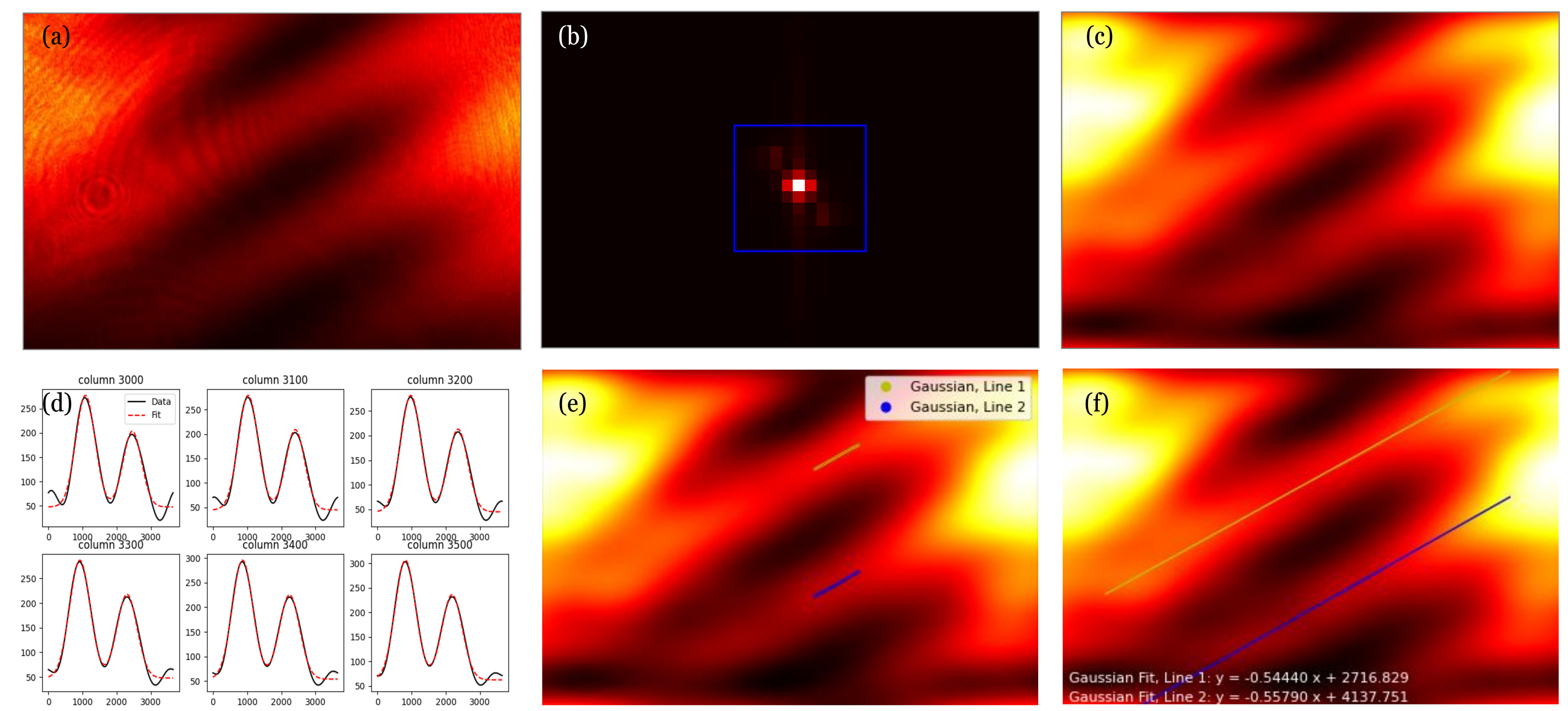


Fig. 4 – Steps of the Linear Fit method.
(a) Images of the fringes are captured and co-added; (b) The FFT of the co-added data is done, and only low frequency signals are kept; (c) The iFFT is done to produce a filtered image; (d) A gaussian is fit to the fringes of the filtered image; (e) The centers of the fringes are plotted; (f) The gaussian centers are fit using a straight line. The slope of the line(s) can be used to calculate the fringe deviation angle.

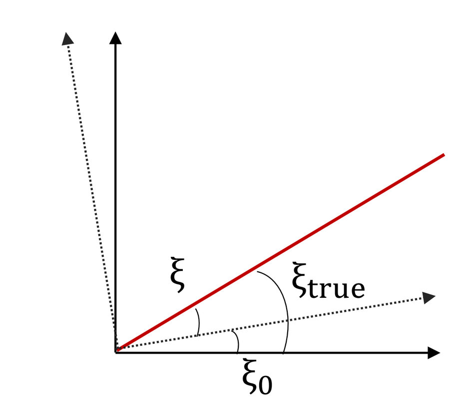
This technology demonstration found that the Linear Fit method achieved a fringe deviation angle error as low as $d\xi = 0.08°$ from experimental data. The error can be reduced further if a larger range of the fringe is sampled (requiring edge noise to be reduced) and if more fringes are present. On a perfectly manufactured "ideal" fringe diagram, a fringe deviation angle error of $d\xi = 0.004°$ was achieved.

Calibration Considerations

The *measurement error* of the angle from the image data, ξ, with respect to the reference was determined. Now, our knowledge of the reference must be considered due to:

- *alignment error* between the angle of the wedge plate and the CCD pixels, ξ_0
- *alignment error* in the translation of the wedge plate in its roll-pitch-yaw stage relative to the CCD

The alignment error ξ_0 is unlikely to be perfectly known, but the shearing interferometer can be **calibrated** with a perfectly collimated beam to obtain the value of ξ_0.



References

[1] Dubey, Rajiv, and Raj Kumar. "Comparison of sensitivity to beam collimation of the holographic shearing interferometer with the wedge plate shearing interferometer and the Talbot shearing interferometer." *JOSA A* 37.9 (2020): B36-B45.

[2] Riley, M. E., and M. A. Gusinow. "Laser beam divergence utilizing a lateral shearing interferometer." *Applied optics* 16.10 (1977): 2753-2756.

[3] Thorlabs. *Shearing Interferometers*. Accessed May 13, 2022 from https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2970