Fundamental Methods to Measure the Orbital Angular Momentum of Light

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CHAPTER 4

Measuring optical vortices in a speckle pattern using a multi-pinhole interferometer

We show that it is possible to find and characterise optical vortices in a speckle pattern using a multi-pinhole interferometer. This measurement does not require an additional flat wave front to interfere with the speckle, providing great experimental ease. In addition, a multi-pinhole interferometer can be made arbitrarily large and can therefore be adjusted to the expected speckle size. We present experimental results confirming our understanding.

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4.1 Introduction

Speckle patterns are very common in optics, since they occur when coherent light is scattered by a rough surface or an inhomogeneous medium [34]. The rough texture of the surface or medium causes the scattered light to interfere in a random fashion resulting in the well-known granular far-field intensity patterns.

The theory of speckle is well established [35]. Due to the random nature of the interference, points exist in a speckle pattern where the field amplitude is equal to zero and the phase is singular. Around these singular points, the field is proportional to $\exp(i\ell\phi)$, or, in other words, the phase varies in an azimuthal fashion, forming an optical vortex [10]. Optical vortices are generally associated with orbital angular momentum [1]. Many experimental and theoretical studies have been performed on the optical vortices in speckle patterns [8, 28, 30, 36–38]. Optical vortices in speckle mostly have topological charge ± 1, however very rare doubly degenerate vortices have been observed [36]. Contrary to the optical vortices in Laguerre-Gaussian beams, the vortices in speckle patterns are anisotropic, meaning that the phase of the field does not increase linearly with the azimuthal angle around the singularity [9, 32]. The phase distribution in speckle patterns may be studied experimentally by interfering the pattern with a flat wave front [8]. The position of the vortex shows up as a fork-like structure in the interference pattern with its topological charge given by the orientation of the fork.

Recently it was suggested that light from astronomical sources could posses orbital angular momentum [11, 26, 39, 40]. One of the most likely fields to contain this orbital angular momentum is a speckle pattern caused by starlight scattering from a inhomogeneous interstellar medium [11]. Studying these patterns could reveal interesting new information about the star and the interstellar medium. Because of the large distance between the scatterer and the detector, these speckles are expected to be large compared to available detectors, making it impossible to study them by interference with a flat wave front.

We recently studied an alternative way to find and characterise optical vortices, that is based on measuring and analysing the interference pattern behind a multipoint interferometer, which consists of a finite number of small apertures arranged in circular fashion [27]. We showed that the interference pattern contains information on the vorticity of the optical vortex impinging the apertures. Guo et al. [41] developed an efficient analysis to extract the relative phases of the light at the individual apertures by performing a Fourier transform on a single interference pattern. Because the system is based on a finite number of pinholes, the light throughput is inherently not very high, making it less suitable for applications at low light levels. In this paper we demonstrate experimentally that the multi-pinhole interferometer, in combination with the Fourier transform method to analyse the interference pattern, can be used to measure vorticity in a speckle pattern, opening the way to do this on a variety of sources including astronomical.

To demonstrate this method experimentally, we measured optical vortices in the lab-

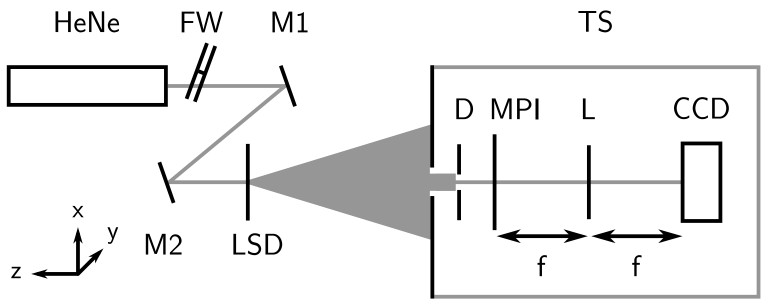

Figure 4.1: Schematic drawing of the setup that is used to measure optical vortices in a speckle pattern. A helium-neon laser (HeNe), appropriately attenuated with a neutral density filter wheel (FW), and two mirrors (M1 and M2) are used to illuminate a small part of a light shaping diffusor (LSD) which creates the speckle pattern. At a sufficiently large distance to guarantee fully developed speckle, a multi-pinhole interferometer (MPI), a lens (L) and a CCD camera (CCD) are placed on a translation stage (TS) that can be moved in the x and y-direction. Several multi-pinhole interferometers with different number of pinholes, pinhole separation and pinhole diameter are combined on a single optical component and a diaphragm (D) is used to select one.

oratory using pinholes, forming a multi-pinhole interferometer [42]. One could also think of replacing the points by telescopes and using recombination optics to overlap the light from the different points. In principle, any given point separation would be possible in this way, making it also suitable for the case that the speckle is much larger than a single detector. We proved theoretically that this method is sensitive to detect anisotropic optical vortices and found that the vortex can be identified as long as the singularity is enclosed by the multipoint interferometer [43]. In this paper, we verify this statement by measuring the position and vorticity of optical vortices in a speckle pattern.

4.2 Experiment

To demonstrate the use of a multi-pinhole interferometer for measuring optical vortices in a speckle pattern, we built a setup as shown in figure 4.1. We illuminate a light shaping diffuser, a specially designed ground glass plate, by a helium-neon laser to create a speckle pattern. At a sufficiently large distance to guarantee fully developed speckle, a multi-pinhole interferometer is mounted on a translation stage. The stage further holds a lens and a CCD camera to record the far field interference pattern behind the multi-pinhole interferometer. The translation stage can be moved in the x and y-direction. In this paper we only present the results for a scan in one direction since we believe that this gives the clearest demonstration of the principle.

A multi-pinhole interferometer consists of N pinholes uniformly distributed on a circle with radius b. As shown in [27], the interference pattern behind such an interferometer contains information on the vorticity of the illuminating optical field for $N \geq 4$ and the number of vortex modes that can be detected depends on N. For an odd number of pinholes, N different vortex modes can be distinguished, while this reduces to $N/2+1$ modes for an even number of pinholes as one cannot distinguish between positive and negative values of ℓ in this case. In a speckle pattern, one only expects vortices with $\ell = \pm 1$. For the above reasons, a multi-pinhole interferometer with $N = 5$ is used in this experiment, which allows detection of optical vortices with $\ell = 0, \pm 1, \pm 2$.

The distance between the light shaping diffusor an the multi-pinhole interferometer is chosen such that the generated speckle is fully developed and that the average distance between two speckles at the interferometer is $X_{sp} \sim 1$ mm. The radius of the interferometer is $a = 100$ μm, which is much smaller than the average speckle size to reduce the possibility that two vortices impinge the multi-pinhole interferometer at the same time. The diameter of the pinholes is $b = 50$ μm, which is the largest pinhole diameter available to garuantee as much throughput as possible. In this experiment, the translation stage is moved in the x-direction over 3 mm and the interference pattern is recorded after every 50 μm. Around the positions where the interference pattern changes because of the presence of an optical vortex, the distance between two consecutive measurements is reduced to 10 μm to improve the resolution.

Direct measurement of the speckle field intensity in the point under study is not possible in the current setup. Instead we determine the total intensity in the recorded interference patterns which is proportional to the total intensity in a small ring around the point under study. Since the intensity around a singularity varies approximately linearly with the distance from the singularity, a minimum in the total intensity in the image implies a minimum in the field intensity at this point.

4.3 Results

Figure 4.2 shows the interference patterns behind the multi-pinhole interferometer at two different positions in the speckle pattern. By comparing these patterns to the patterns published in [27], one can see that the interference pattern in figure 4.2 (a) corresponds to the pattern for an optical vortex with $\ell = 0$, while figure 4.2 (b) resembles the interference pattern for an optical vortex with $\ell = -1$. The orientation of the patterns is determined by the orientation of the multi-pinhole interferometer with respect to the CCD camera. The Fourier transform analysis as presented by Guo et al. allows a quantitative analysis of these interference patterns [41].

Due to the random nature of the fully developed speckle pattern, the local propagation direction of the light impinging the multi-pinhole interferometer varies, causing the interference pattern to move on the CCD-camera. Before the Fourier transform analysis is applied, the interference pattern is first centred on the image.

Guo et al. showed that the relative phases ψ at the pinholes can be determined from the phase of the Fourier transform of the interference pattern behind a multi-pinhole interferometer. They showed that the relative phases can be extracted from the vertices of a polygon, that is a scaled and shifted copy of the multi-pinhole interferometer. Since we

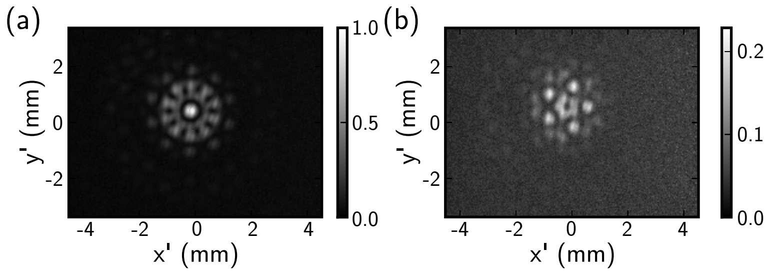

Figure 4.2: Interference patterns behind the multi-pinhole interferometer recorded at two different positions in the speckle pattern. (a) shows the interference pattern at relative position $x = 0$ mm, a region of high field intensity. (b) shows the interference pattern at relative position $x = 1$ mm, a region of low field intensity. The changing pattern is explained by an optical vortex impinging the multi-pinhole interferometer in (b). The size of each pixel in the CCD image is 6.5 µm and both images contain 1392×1040 pixels. Both images are recorded using the same settings of the CCD-camera and are normalised to the peak intensity of image (a), allowing a direct comparison of the total intensities in the images.

use a multi-pinhole interferometer with five pinholes, the polygon is in fact a pentagon.

Figure 4.3 (a) shows the phase of the Fourier transform of the interference pattern in 4.2 (b). For clarity the aforementioned pentagon is overlaid on the phase of the Fourier transform. Due to the symmetry of the multi-pinhole interferometer, this pentagon can be drawn in ten different orientations (not drawn in figure 4.3 (a)). To reduce the effect of the noise, we determine the relative phases at the pinholes for each of the ten different orientations of the pentagon and average these. Figure 4.3 (b) shows the average relative phases for figure 4.3 (a), where ϕ denotes the azimuthal angle, and gives a comparable result to figure 3 (b) in [41], showing that the optical vortex impinging the multi-pinhole interferometer in this case has topological charge $\ell = -1$. The vorticity of the field impinging the multi-pinhole interferometer is determined by fitting a line through the averaged phase profile and determining the value of the fit at $\phi = 2\pi$.

In total 93 interference patterns were recorded as a function of position in the speckle pattern. Figure 4.4 shows the results of the data analysis for all these patterns. The total intensity in each image is shown in figure 4.4 (a), where the curve is normalised to its maximum and shows two minima. The minimum around $x = 1$ mm corresponds to the image shown in figure 4.2 (b). From figure 4.4 (b) it is clear that this position can be associated with an optical vortex of topological charge $\ell = -1$. The minimum at $x = 2.6$ mm proves to be associated with an optical vortex of topological charge $\ell = 1$ (see Fig. 4.4 (b)). The width of the plateau of both peaks in figure 4.4 is ~ 100 µm, which confirms the fact that an optical vortex can be observed as long as its axis lies well within the multi-pinhole interferometer.

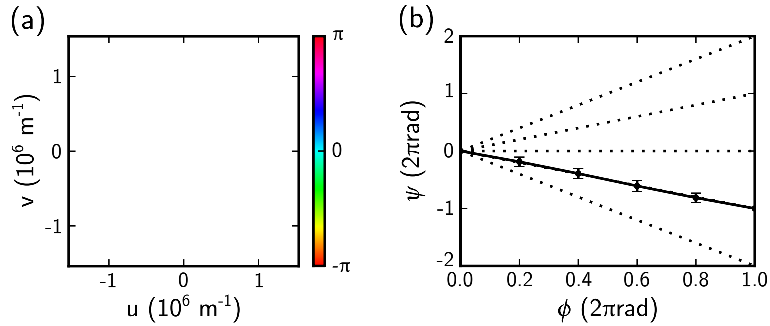

Figure 4.3: (a) Phase of the Fourier transform of the interference pattern in figure 4.2 (b). As a guide to the eye the positions where the relative phase is read off are shown as the vertices of the white pentagon. The same pentagon can be drawn in ten different orientations. (b) shows the average phase at the individual pinholes ψ calculated from the ten different orientations as a function of the azimuthal angle ϕ. The dotted lines are drawn as a guide to the eye and indicate the relative phases for optical vortices of topological charge $\ell = 2, 1, 0, -1, -2$ from top to bottom.

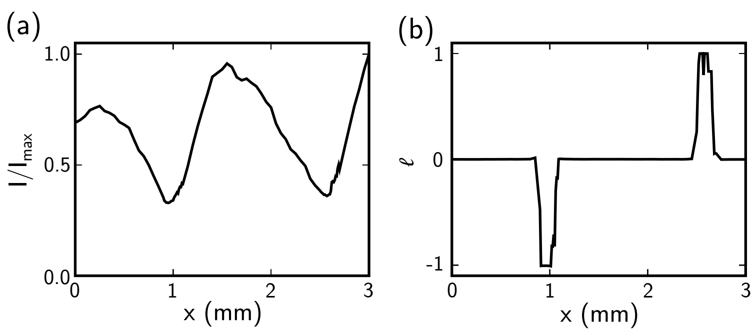

Figure 4.4: (a) Normalised total intensity in the recorded interference patterns as a function of multi-pinhole interferometer position x. Since this intensity is proportional to the intensity in a small ring around the vortices, it is expected not to go to zero. (b) Vorticity of the field imping-ing the multi-pinhole interferometer as calculated using the Fourier transform analysis. The two minima in (a) clearly correspond to optical vortices of opposite sign.

4.4 Discussion

We demonstrated that a multi-pinhole interferometer is an efficient tool for finding and characterising optical vortices in a speckle pattern. The main advantage of this technique is in the fact that it does not require an additional flat wave front to interfere with the speckle. In addition, this method relies only on a finite number of point measurements and can therefore be scaled to arbitrary sizes, making it applicable to the case where the speckle pattern is much larger than the detector area. The pinholes can be replaced by telescopes and optics to combine the light from them. For electromagnetic fields at lower frequencies wave pipes or electronics can be used to transport and combine the signals.

An important application is foreseen in finding optical vortices in speckled astronomical wave fronts. A more detailed study has to be performed on the exact nature of the speckles that can be expected in astronomical wave fronts.

Some care has to taken in choosing the separation between the pinholes or telescopes. The average speckle size determines both the lower and upper limit of this separation. The pinholes cannot be placed too close to the vortex, since there is hardly any intensity. On the other hand, as the pinholes are placed too far apart, neighbouring vortices start to affect the measurement. We found that a pinhole separation that is roughly one tenth of the average speckle size is a good trade-off.

Combining a large number of multi-pinhole interferometers in a single array would make it possible to find a large number of optical vortices in a wave front in one measurement. Knowledge of the position and vorticity of these vortices makes it possible to reconstruct the wave front, making such an array suited to be used as a wave front sensor. The ability to detect optical vortices is an advantage over existing wave front sensors like the Shack-Hartmann sensor, although a more detailed study has to be carried out to compare the performances of both sensors.

4.5 Conclusion

We demonstrated that a multi-pinhole interferometer, using only a finite number of apertures, can be used to quantitatively map the vorticity in a fully developed speckle pattern. To our understanding this is the first method to measure optical vortices in a speckle pattern without the need for a reference wave front. In addition a multi-pinhole interferometer can, in principal, be scaled to arbitrary sizes, which allows measurement of optical vortices in speckle patterns with any given speckle size.