Sensitive measurement of partial coherence using a pinhole array

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1. Introduction

For applications which require partially coherent light, e.g. in miniaturized interference setups like micro-imaging systems, the area of spatial coherence should fit to the optical design. For example, we apply partial coherence to lenseless inline holographic microscopy [1-3]. Even if high coherent sources are suitable for the requirements of interference, a high degree of coherence is responsible for many disturbing effects within the optical system. Especially statistical interferences due to rough surfaces, so called speckles, are generated by coherent light [4, 5]. Unwanted reflections from optical surfaces and their interferences limit the quality of measurement.

An area of coherence can be defined as an area of featured interferences. The coherence volume can be defined as the product of the coherence length and the area of coherence. It is helpfull to use light sources with coherence volumes which correlate with the dimension of the setup itself. When only a small coherence volume is required, even partial coherent light sources, like halogen lamps or mercury lamps, are qualified to comply with the requirements of interference. Therefore it is necessary to determine the degree of coherence of those partially coherent light sources.

Spatial coherence is measured by Young's double slit interferometer [6]. The measurement range is given by the pinhole distance and the throughput is given by the pinhole diameters. In the case of small areas of spatial coherence this setup is limited in sensitivity. A sensitive measurement and management of partial spatial coherence is often necessary. The current task is to develop an interferometer for a much more sensitive measurement of partial spatial coherence with an extended measurement range for small areas of spatial coherence.

2. Double pinhole interferometer

The working principle of Young's double slit interferometer is shown in figure 1. A suitable light source illuminates two pinholes in the aperture plane. A lens is used as a condensor. Every single pinhole generates a cone of light as diffration pattern. Assuming the pinholes are circular, the single diffraction pattern can be characterized as an Airy-like diffraction figure in the detector plane. In far field, these two diffraction patterns overlay. If the light is spatially coherent, interference fringes can be observed in the detection plane. Due to the geometry of the optical setup, an interference pattern with dark and bright fringes is enveloped by the diffraction pattern of a single pinhole. The interference pattern is descibed by two-beam interference

$$I_{sum} \cong I_1 + I_2 + 2\sqrt{I_1 I_2}\,\gamma_{12}\cos\left\{\left(k_1 - k_2\right) r + \Delta\varphi_{12}\right\}, \tag{1}$$

where I_1 and I_2 are the single pinhole intensitys distributions, γ_{12} is the degree of spatial coherence. For equal intensities $I_1 = I_2$ of both pinholes, the modulus of γ_{12} can be determined directly by measuring the visibility V of the fringes

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \left|\gamma_{12}\right|. \tag{2}$$

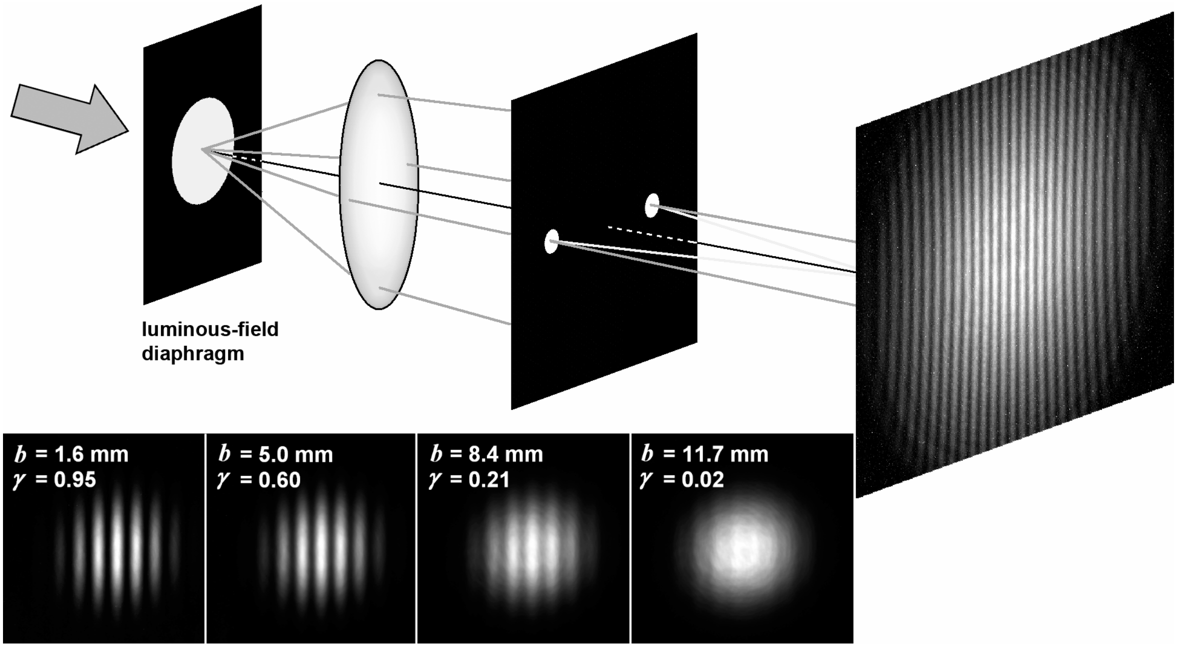

Fig. 1: Scheme for Young's double pinhole interferometer to determine the degree of spatial coherence: The interference pattern of the double pinhole is shown. The contrast of fringes correlates with spatial coherence. The diameter of the luminous-field diaphragm determines the degree of spatial coherence. In the measured example (part below) the degree of coherence varies between 0.95 and 0.02 adjusted by the diameter b of the luminous-field diaphragm of a microscope between 1.6 mm and 11.7 mm. A double pinhole with a distance of 8 µm and a pinhole diameter of 1.2 µm is used.

The degree of spatial coherence is theoretically determined by the theorem of van Cittert and Zernike [7, 8]. In the case of double pinhole interference and assuming a circular light source, the functional correlation between the degree of spatial coherence and the size of the source is given by

$$\gamma_{12} = \frac{2\, J_1(\nu)}{\nu}; \qquad \nu = \pi \frac{b\, d}{\lambda_0\, f}, \tag{3}$$

where J_1 is the Bessel function of the first kind and first order, b is the diameter of the source, d is the distance between the pinholes, f is the focal length of the illumination lens and λ_0 is the used wavelength.

Due to the shape of the Bessel-function, there is no exact value to define the size of the coherence area. In literature different definitions are given, e.g. $\gamma_{12} \approx 0.88$ if $\upsilon = 1$ [9] (see criterion (a) in fig. 2).

In case of small coherence areas it is necessary to optimize the parameters of the sensor (the double pinhole) according to the measurement range. Without influencing the optical system, the distance of the double pinhole must be reduced down to some microns. The diameter of the pinholes must decrease simultaneously. While reducing the diameter of the pinholes, the optical throughput decreases rapidly too. So, the available intensity for measurement is very low and the signal-to-noise ratio becomes insufficient. Especially in the case of low intensity light sources, e.g. halogen lamp, the signal-to-noise ratio can reach one.

Experiments are made with a microscope (Axioscope from Zeiss) in combination with an EC Epiplan NEOFLUAR 20x/0.5 HD DIC lens. A mercury HBO lamp and a halogen lamp are used for illumination in combination with a spectral filter at 546 nm with a bandwidth of 12 nm. The spectral filter ensures the temporal coherence, which is necessary for interference. For data acquisition a 12 bit CCD camera is used. The luminous-field diaphragm and an additional diffuser represent a secondary light source within the microscope. While modifying the diameter of the luminous-field diaphragm the size of the area of spatial coherence within the pinhole plane is influenced.

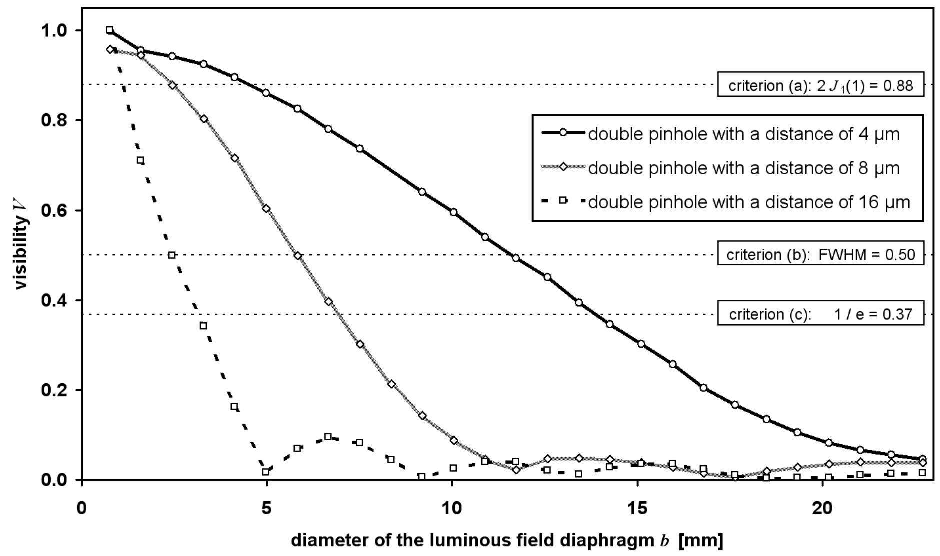

Fig. 2: Spatial coherence, measured by the visibility of interferences in dependence on the diameters of the luminous-field diaphragm for the described setup. Double pinholes (see fig. 1) with distances of the pinholes of 4, 8 and 16 µm are used. A spectral filtered mercury lamp is used (λ = 546 nm, $\Delta\lambda$ = 12 nm).

Figure 1 (lower part) shows measurements of two-beam interferences for different degrees of spatial coherence. The degree of spatial coherence is adjusted by the diameter of the luminous-field diaphragm b. The pinhole distance was fixed to 8 µm and the pinhole diameters were 1.2 µm. To determine the degree of spatial coherence the visibility of interference fringes is measured.

As figure 2 shows, the measurements of the degree of spatial coherence fits to the theory mentioned in [6] and equation (3). For very small diameters of the luminous-field diaphragm, the degree of spatial coherence is high. The gradient of the degree of spatial coherence is increased with rising distance of the double pinhole.

The definition of an area of coherence requieres a typical value for interference visibility. In figure 2 corresponding examples are given (see criterions (a)-(c)). Criterion (a) with a degree of spatial coherence of 0.88 may fit best for holographic applications with very high contrasts. With less degrees of coherence criterions (b) or (c) are commenly used, too. Criterion (b) is chosen for our further measurements. For fixed pinhole distances a correlation between the diameter of the luminous-field diaphragm and the diameter of the area of spatial coherence can be defined.

3. Pinhole array interferometer

The idea of improving Young's double pinhole test is to increase the number of constructive interferences. Multi-beam interferences can result in maximum intensity factors of $N^2/4$ in comparison to the double pinhole (N is the number of pinholes). They are generated by a pinhole array. The intensity of the interference pattern can be written in an analog form compared with the double pinhole by

$$I_{sum} = \sum_{i=1}^{N} I_i + 2\sum_{i=2}^{N}\sum_{j=1}^{i-1}\sqrt{I_i I_j}\,\gamma_{i,j}\,\cos\left\{\left(k_i - k_j\right)r + \Delta\varphi_{i,j}\right\}. \tag{4}$$

Constructive multi-beam interferences appear in different planes. The Talbot effect is known as an effect of multi-beam interferences, which also depends on the coherent addition of single waves. A periodic array of pinholes generates periodic interference patterns in all three dimensions. This pattern is described by the fractional Talbot effect [10, 11].

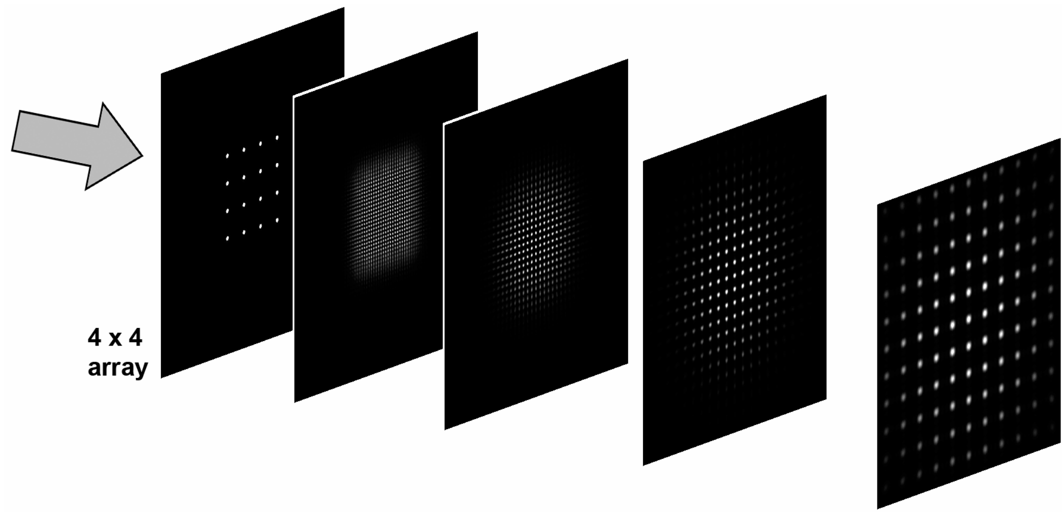

Fig. 3: Diffraction pattern of a 4 x 4 pinhole array with increasing distances to the array (z = 0, 52, 103, 206 and 412 µm). The Talbot plane (1/2) is localized at 412 µm (λ = 546 nm). The pinhole diameters are 1.2 µm and the periodic distances are 15 µm.

Planes with best contrast are Talbot planes, localized at focal distances $z = L_{\mathrm{Talbot}}$ along the optical axis at

$$L_{Talbot} = \frac{1}{q}\frac{d^2}{\lambda_0}, \tag{5}$$

where d is the periodicity of the pinholes and q is an integer.

Because the array contains only a finite number of pinholes, its diffraction pattern is Talbot-like only in an area near to the optical axis and within the distance of the first unfractured Talbot plane (fig. 3). For an infinite number of pinholes the Talbot-effect would fill the whole space with the periodic diffraction pattern.

The interference pattern changes for partially spatially coherent light. The interference spots spread larger and reduce in peak intensity simultaneously (fig. 4). Both the contrast and the visibility decrease, but in a different way compared to the double pinhole. From a cut section through a single Talbot plane the visibility of the pattern is determined for different degrees of spatial coherence.

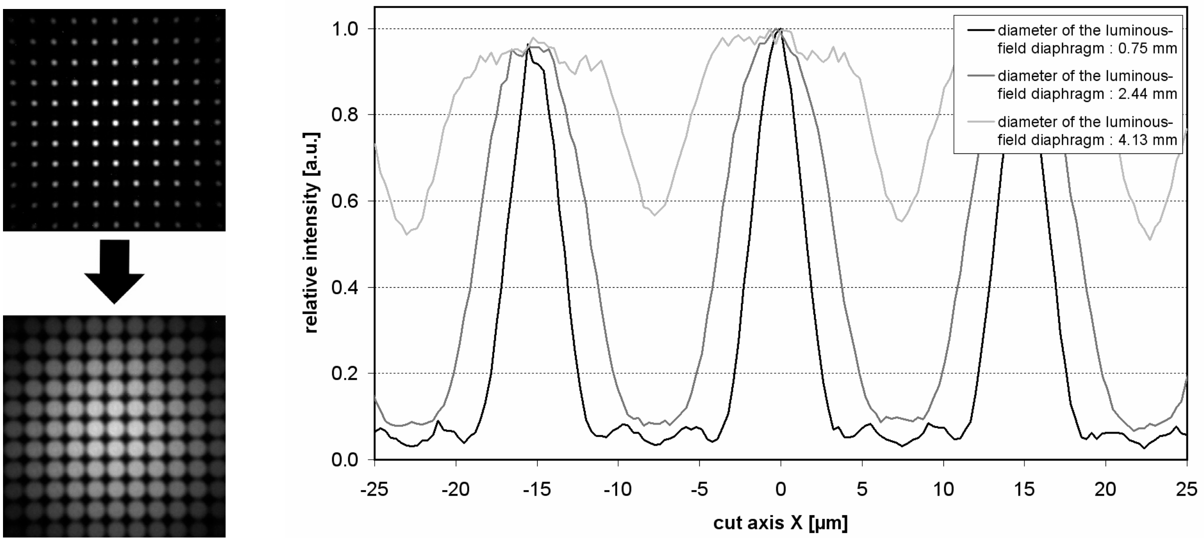

Fig. 4: Determination of the degree of coherence in dependence on the measured diffraction pattern. A high contrast correlates with a high degree of spatial coherence.
The Talbot plane (1/2) at 412 µm focal distance is used. Illumination is made with a halogen lamp and a spectral filter at 546 nm, bandwidth 12 nm.

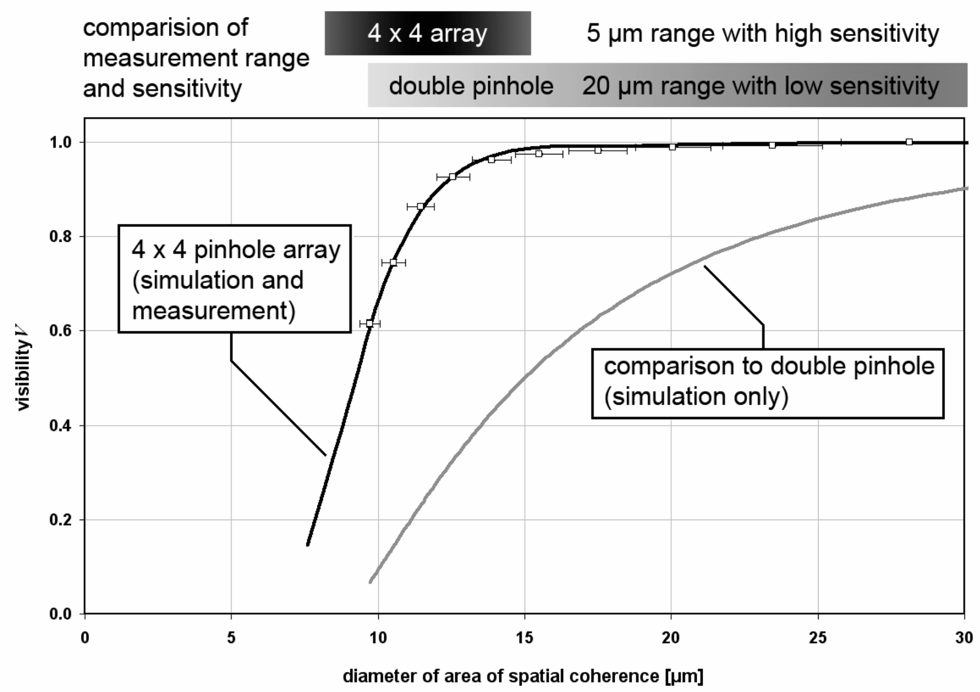

Fig. 5: Sensitivity of measurement of partial spatial coherence using the pinhole array interferometer: Visibility of interferences in dependence of spatial coherence for the 4 x 4 pinhole array interferometer compared with the double pinhole interferometer. The sensitive measurement range is shifted to a smaller degree of coherence and the gradient of visibility is increased (5 µm measurement range with a sensitivity of 0.212/µm for the 4 x 4 array, 20 µm measurement range with an average sensitivity of 0.053 µm for the double pinhole).

The degree of spatial coherence is in general defined by the cross-correlation of only two points. But, of course, it is possible to measure the visibility in the same way as for the double pinhole also for a 4 x 4 pinhole array (fig. 5). The pinhole diameters are 1.2 µm and the distances are 15 µm. A mercury HBO lamp is used for illumination. The area of coherence can be determined more precisely because of the characteristic sharp interference fringes. The increased gradient of the visibility yields a higher sensitivity for measuring the area of spatial coherence. Compared to the double pinhole the gradient is increased by a factor of 4 using the 4 x 4 pinhole array. It is possible to measure smaller areas of spatial coherence from 10 to 15 µm in diameter with higher sensititvity. The measurement range can be chosen by the periodic distance of the pinholes.

4. Summary

The degree of spatial coherence is measured by Young's double pinhole interferometer and also by the presented array interferometer. A 4 x 4 pinhole array is used with 1.2 µm pinholes with distances of 15 µm. The number of constructive interferences is increased by the array interferometer. Compared to the double pinhole the peak intensity is increased by a factor of $N^2/4$ (N is the number of pinholes within the array). The signal-to-noise ratio is also improved. The measured enhancement of peak intensity is a factor of 54 for the 4 x 4 pinhole array. The theoretical limit is a factor of 64 assuming far-field interferences with a degree of coherence of one.

The sensitivity for measuring spatial coherence is determined by the gradient of the visibility and is enhanced by a factor of 4 compared to the double pinhole. The measurement range with high sensitivity is shifted to smaller areas of coherence and can be adjusted by the distances within the pinhole array. The area of spatial coherence for a halogen lamp and a mercury lamp was in a range from 10 to 15 µm.

The intensity enhancement can be increased further by using a larger number of pinholes in the array. The pinhole distances can be decreased down to some microns to measure areas of spatial coherence of a few microns.

We use the technique to adjust the degree of coherence for holographic microscopy and to avoid aberrations caused by interferences between the optical planes of the devices.

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