# Efficient Measurement of Nonstationary Complex Coherence Functions

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**Abstract:** We demonstrate an accurate, two-step procedure for measuring the full complex coherence function. The measurement relies on a wavefront shearing interferometer that permits characterizing nonstationary fields over an extended angular domain.
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**Introduction:** The spatial coherence function (SCF) of an electromagnetic field can be measured using both non-interferometric and interferometric methods. Wigner distribution non-interferometric measurements require a resolution tradeoff between the spatial and angular sampling. Interferometric methods access directly the field correlation functions and can be implemented based on either wavefront sampling or wavefront shearing approaches. The wavefront sampling approach relies on the classical setting of Young's two pinholes or on a variety of redundant or non-redundant arrays of pinholes and multiple aperture masks [1-3]. The alternative technique, wavefront shearing, can be implemented using a variety of interferometric settings such as the common path Sagnac or grating shear interferometers [4-6]. Here we report a wavefront shearing measurement in which the real and imaginary parts of the coherence function are obtained through only two measurements. The measurement is based on the lateral shearing of two copies of optical wavefront that counter-propagate through a common physical path. To demonstrate the capabilities of this interferometer, we measured the coherence function for broad-bandwidth light emitted from differently shaped, equal-area sources. Excellent agreement with theoretical predictions was also demonstrated.

**Dual-Phase Sagnac Interferometer (DuPSaI):** For measuring the complex spatial coherence function (SCF), we developed a system we will refer to as DuPSaI which combines a telescopic imaging system with a Sagnac interferometer [4]. In our approach, the polarized monochromatic beam is separated into two identical copies through a non-polarizing 50/50 beam splitter. These copies counter-propagate along a common path which consist of two flat mirrors, a half-wave plate and a quarter wave plate as shown in Figure 1. A symmetrical lateral shear, $s$, is introduced with respect to the original position by synchronized movement of mirrors while maintaining the original path length. A phase delay is introduced by rotating the half wave plate. The interference pattern resulting from the interference of the two field replicas are imaged onto an EMCCD (Andor Xion 888). This scheme has the benefit of using the entire optical field impinging on its input aperture. In order to obtain both the real and the imaginary part of the SCF, we first record a series of intensity patterns for multiple shearing distances $s$ while the fast axes of each wave plate are parallel with the direction of incident polarization: $I^0(x,2s) = I(x+s) + I(x-s) + 2\mathrm{Re}[\Gamma(x+s,x-s)]$. A $\pi$ phase differences is then introduced between the two interfering waves by rotating the half-wave plate by $\pi/4$ radians and a second series of intensities is obtained: $I^{\pi/4}(x,2s) = I(x+s) + I(x-s) + 2\mathrm{Im}[\Gamma(x+s,x-s)]$.

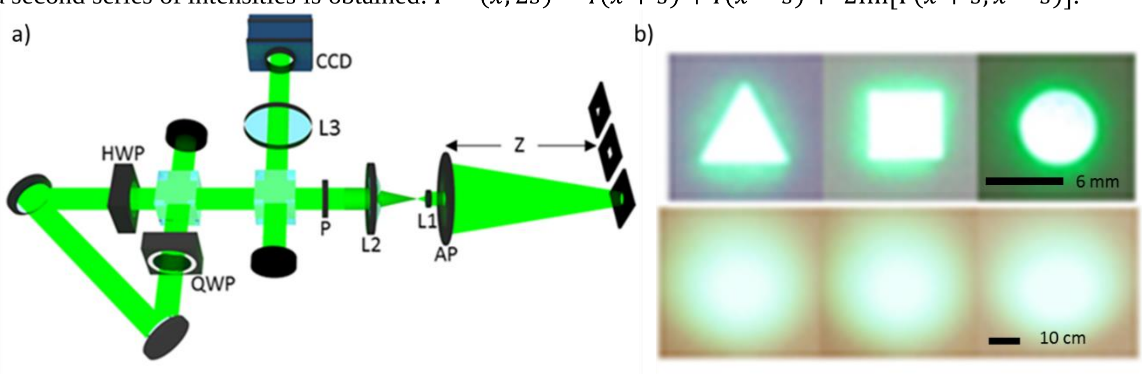


Figure 1. (a) Schematic of experimental setup for measuring SCF at the plane of the input aperture AP. The source is a green LED with 30 nm bandwidth centered at of 525 nm and placed at Z= 1m from AP. Differently shaped sources are created using apertures placed at the output plane of the source. The other elements are: L1, L2, L3 lenses, (HWP) half-wave plate, (QWP) quarter-wave plate, and P polarizer. (b) The intensities recoded in the plane of the source (top) and at a distance of 20cm (bottom).

Traditional interferometric techniques would require two additional measurements to retrieve the complex SCF [4]. In our approach, we took advantage of certain properties of a common-path interferometer to accomplish this task with only two orientations of the wave plate. At zero shear, $\mathrm{Re}\big(\Gamma(\mathrm{x},\mathrm{x})\big) = I(x)$ and $I^0$ becomes $4 \cdot I(x)$. Further, one can obtain the real and imaginary components of SCF to be:

$$\mathrm{Re}[\Gamma(x+s,x-s)] = 0.5\big(I^0(x,2s) - 0.5\, I^0(x,0)\big)$$
$$\mathrm{Im}[\Gamma(x+s,x-s)] = 0.5(I^{\frac{\pi}{4}}(x,2s) - 0.5\, I^0(x,0))$$

**Experimental demonstrations:** To establish the measurement accuracy, we constructed three apertures with different shapes (circle, square, and equilateral triangle), but having all the same area of $2.83 \times 10^{-5}\ \mathrm{m}^2$ to emulate sources emitting the same amount of power within the same spectral range. In the experiment, the apertures were illuminated by a high power LED (Thorlabs, Solis-525C) and were placed at 1m distance from input aperture of the interferometer. Using the procedure outlined before, we were able to measure both the magnitude and phase of SCF over the wavefront extent of 4 mm. As can be seen in the intensity distributions shown in Figure 1a, the shape of the source is already lost at 20cm away from the source. However, quite different coherence functions are being detected at 100cm from the source as seen in Figure 2. When compared with the calculations based on Fresnel integrals, a reasonable agreement is found for the first and second minima of the main coherence lobes corresponding to different shapes (Figure 2b). Even though the sources have the same area, we note that the length of the averaged chord ($\bar{x}$) of the source aperture parallel to the direction of shear are different: 5.32mm for the square, 4.76mm for the disk, and 4.04mm for the triangular source. These values are inversely proportional to the location of the first SCF minimum, as expected, and demonstrate the ability to discriminate between shapes of sources having the same areas and same emitting powers along a lateral scale of 4 mm. Another advantage of the wide-field measurement is the ability of detection nonstationary (spatially varying) SCF. In our case nonstationarity manifested in a phase variation across the image that served as indication of the source location. We will demonstrate that the DuPSaI is capable of measuring the SCF ranging from 4 microns to over 1 mm.

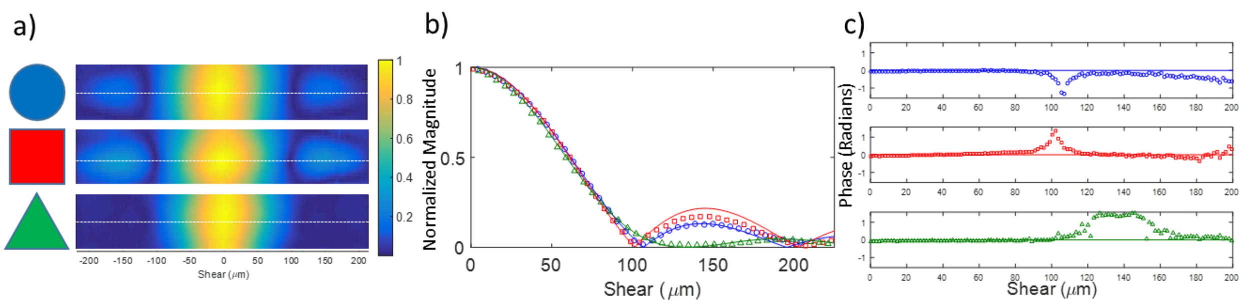


Figure 2.(a) Measured magnitude of 2D coherence function corresponding to different source shapes. (b) Cross-sections of part (a) along the white dotted lines (market lines), together with corresponding calculations using the Fresnel integral (solid lines). (c)The corresponding SCF phases.

**Conclusion:** In conclusion, we have developed an efficient interferometric device capable of measuring the complex coherence function. Reliable coherence measurements can discriminate between shapes of radiation sources in conditions where the intensity distributions contain no useful information. Wide-field coherence measurements also allowed detecting nonstationary field properties and permit locating the center of mass of the source of optical radiation.

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