# Synthesis of structured partially spatially coherent beams

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Received January 20, 2011; revised March 25, 2011; accepted March 26, 2011;
posted March 30, 2011 (Doc. ID 141478); published April 28, 2011

We report on the generation and rapid characterization of structured beams of arbitrary spatial coherence. An experimental setup is introduced capable of generating partially coherent fields by incoherently superposing fully coherent fields. The characterization is performed using the spectral information in the interferogram produced when using a two-dimensional nonredundant array of pinholes. An example of a partially coherent "doughnut" beam is given and proved to be partially coherent. © 2011 Optical Society of America

*OCIS codes:* 030.1640, 030.4070, 070.4790, 090.1995, 120.3180.

The coherence of light has played an important role in the science of understanding and tailoring the effect that light has on matter. It is well known that variations in an electromagnetic field can affect physiochemical processes such as collisional events and electron population transfers [1–3]. This fact has a significant impact for example on lithographic writing processes, imaging, optical investigations of molecular dynamics, second-harmonic generation, optical traps, and micromachinery [4–6]. Nonetheless, a relationship between the statistical variations of a field and their effect on matter has yet to be fully established.

Experimental investigations of coherence effects are commonly limited by the extent to which the spatial coherence can be controlled. Typically a lens is used together with a rotating ground-glass diffuser to change the degree of spatial coherence by varying the distance between the lens and the ground glass [7]. Other configurations include a second counterrotating diffuser [8], an enclosed turbulent gas to act as a random diffuser, multimode fibers [9], and time-multiplexed beams with given irradiance profiles [10]. These configurations, however, are limited to generate beams with a homogeneous irradiance and coherence distribution, or require a long integration time to be considered partially spatially coherent, or it is difficult to tailor the degree of coherence. In this Letter we introduce an experimental setup capable of generating quasi-monochromatic fields with an arbitrary transverse distribution of spatial coherence and irradiance. As an example, we generate a partially coherent "doughnut" beam and characterize its spatial coherence properties using a two-dimensional (2D) nonredundant array of pinholes [11].

The setup proposed is based on the theory of coherent mode expansions of a correlation function, which are an extension of Karhunen–Loéve theory commonly found in studies of temporal coherence [12]. Karhunen–Loéve theory states that, given a (Hermitian, nonnegative definite, square integrable) scalar correlation function over a closed domain $\mathcal{D}$ such as the cross-spectral density function $W(\mathbf{r}_1, \mathbf{r}_2, \omega)$, it is possible to expand it in terms of an infinite, orthonormal set of so-called coherent modes, $\phi_n(\mathbf{r}, \omega)$, according to [13]

$$W(\mathbf{r}_1, \mathbf{r}_2, \omega) = \sum_{n=0}^{\infty} \lambda_n \phi_n^*(\mathbf{r}_1) \phi_n(\mathbf{r}_2), \qquad (1)$$

where the coherent modes and associated expansion coefficients $\lambda_n(\omega)$ are found by solution of the Fredholm integral equation:

$$\int_{\mathcal{D}} W(\mathbf{r}_1, \mathbf{r}_2) \phi_n(\mathbf{r}_1) \mathrm{d}\mathbf{r}_1 = \lambda_n \phi_n(\mathbf{r}_2). \qquad (2)$$

Note that use of the cross-spectral density function requires the underlying random process to be wide-sense stationary, which shall be assumed henceforth. By asserting that $\phi_n(\mathbf{r})$ satisfy Eq. (2), each coherent mode is mutually uncorrelated, such that Eq. (1) represents the incoherent superposition of fully spatially coherent fields $\phi_n(\mathbf{r})$. Practical realization of a partially coherent beam can hence be achieved by the superposition of coherent beams from mutually uncorrelated sources.

In our experimental setup the sources consist of a bundle of single-mode fibers emitting the light coupled from a rotating disk diffuser as shown in Fig. 1. The phase and irradiance fluctuations of the coupled light are such that the fluctuations in the irradiance of the emitted light ensures the lack of correlation between the sources (at the time scale of the measurement). Light emitted by the fibers is collected forming 4 mm diameter beams and incident onto a binary spatial light modulator (SLM)

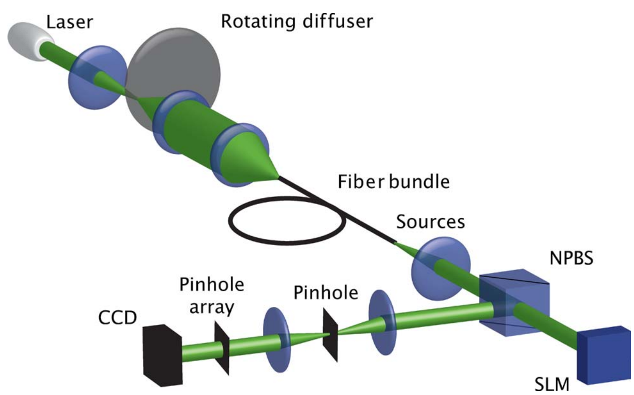


Fig. 1. (Color online) Schematic of the experimental setup proposed for the generation and characterization of structured partially coherent beams. NPBS, nonpolarizing beam splitter.

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(4DD–SXGA-R3) that is located at the back focal plane of the collimator lens. A set of binary holograms are spatially multiplexed onto the SLM, where the orientation and carrier frequency of each hologram is varied so as to modify the complex amplitude of the incident light and the position of the diffraction orders [14]. The number and form of the encoded holograms determines the number and form of coherent modes, which ultimately contribute to the generated beam according to Eq. (1). The desired partially coherent beam is formed by spatially overlapping and filtering the first diffraction order of each fiber. Note that, to make efficient use of the SLM, the fibers at the exit side of the bundle are placed following a curved path as shown in Fig. 2(a). The white box in Fig. 2(a) shows a magnified image of the overlapping diffraction orders. This is a partially coherent doughnut beam focused with a numerical aperture of 0.13.

Note that the maximum number of coherent modes that can be used is restricted by aliasing that depends on the type of SLM being used. The light throughput is given by the diffraction efficiency of the SLM. The spatial multiplexing does not affect the diffraction efficiency given that more sources are included and their diffracted orders are being added. Any nonuniformities present in the fiber bundle can be taken into account in the holograms.

A number of different coherence and irradiance distributions can be generated using the proposed setup. It is possible, for example, to use the setup with spatially coherent and partially spatially coherent sources. If the sources are fully spatially coherent, the modulated irradiance distribution of the sources yields a set of coherent modes as mentioned before. In this case the generated beam will thus have an associated coherence function defined by the user. In the case when the sources are partially spatially coherent, the coherence functions associated with each beam add linearly to form a new coherence function describing a new partially coherent beam. Beams with a coherence distribution structured arbitrarily can also be generated. Figure 2(b) shows for example the irradiance distribution of a partially coherent doughnut beam. This beam was generated by incoherently superposing a Hermite–Gauss (HG) mode $(0, 1)$, mode $(1, 0)$, and mode $(1, 1)$ with equal weights.

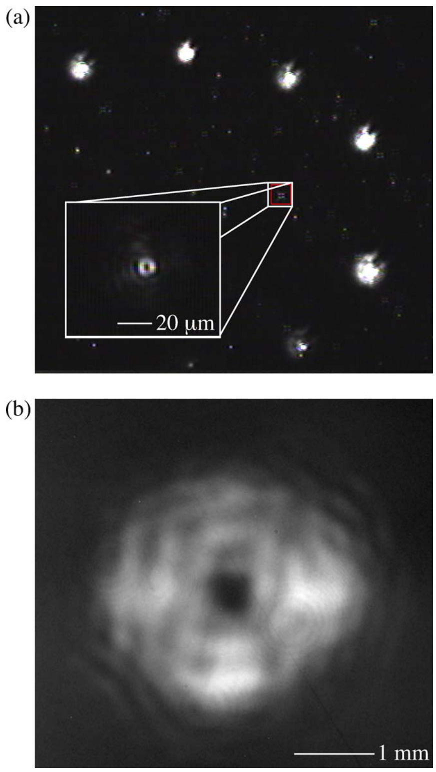


Fig. 2. (a) Curved path described by the fiber bundle at the exit side. The white box is a magnified image of the overlapped orders when creating a partially coherent doughnut beam. The partially coherent doughnut beam is produced by incoherently superposing HG mode $(1, 0)$, mode $(0, 1)$, and mode $(1, 1)$. (b) Irradiance distribution of the partially coherent doughnut beam at the back focal plane of the collimator lens.

The partial coherence of the doughnut beam in Fig. 2(b) can be shown by measuring its degree of spatial coherence. It is customary that the measurement is performed using the well-known double pinhole experiment. In this Letter however, a less cumbersome method is used [11]. The degree of spatial coherence can be obtained from the Fourier spectrum of the interference pattern formed by a 2D nonredundant array of pinholes. The array used here consisted of 62 pinholes of 50 $\mu$m in diameter and positioned at distances ranging from 90 $\mu$m to 3.8 mm. This array yielded 1891 unique pinhole-pair combinations. When illuminating the array, the field emerging from each pinhole interferes in the far field with the fields from the rest of the pinholes. The irradiance distribution resulting from the interference consists of a specklelike pattern whose Fourier spectrum is formed by multiple peaks. By virtue of the nonredundant nature of the pinhole array, the height of each peak is proportional to the fringe visibility of the interference resulting from only two pinholes and hence proportional to the degree of spatial coherence of the fields from those pinholes [11]. The degree of coherence can thus be obtained by weighting each Fourier peak by the reciprocal irradiances of the corresponding pinhole pair (disregarding the conjugate set of peaks).

Note that it is possible to sample the cross-spectral density function from the weighted Fourier spectrum by using the pinhole positions. For our purposes however, consideration of the weighted Fourier spectrum is sufficient. This is because the spectrum represents a mapping of the degree of spatial coherence between a pair of points as a function of their separation and orientation.

Figure 3(a) shows the experimental Fourier spectrum obtained when illuminating the pinhole array with the partially coherent doughnut beam. A greater reduction in the correlation would be expected at regions in which the coherent modes significantly overlap spatially. Correspondingly, an incoherent superposition of HG $(0, 1)$, $(1, 0)$, and $(1, 1)$ modes would be expected to exhibit correlation in the horizontal and vertical directions, with a large reduction in the diagonal directions. Inspection of the experimental Fourier spectrum of Fig. 3(a) indeed corroborates this.

Figure 3(b) shows a numerical simulation of the Fourier spectrum for comparison. It is possible to see that the experimental and theoretical results follow a similar trend. An exact match was not possible however due to the sensitivity of the method to the position of the pinhole array in respect to the beam. Figure 3(c) shows the Fourier

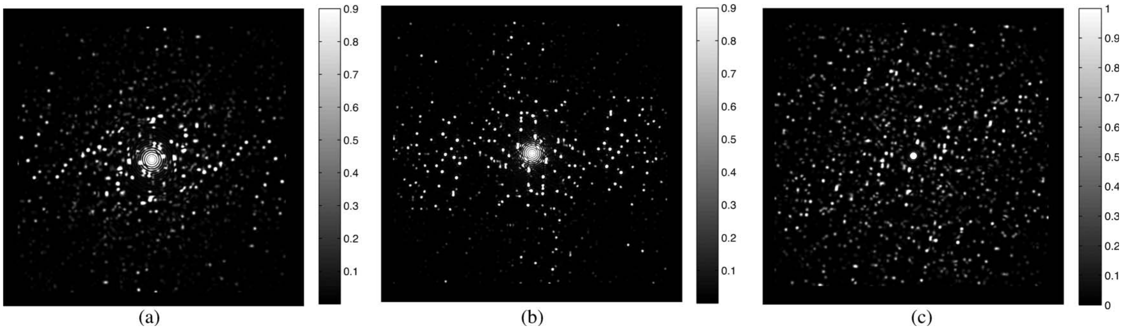


Fig. 3. (a) Fourier spectrum obtained experimentally when illuminating the pinhole array with the generated partially coherent doughnut beam. (b) Theoretical Fourier spectrum expected when illuminating the array with the generated doughnut beam. (c) Experimental Fourier spectrum obtained when illuminating with a fully coherent doughnut beam.

spectrum obtained experimentally when illuminating the array with a fully coherent doughnut beam generated from the coherent addition of the HG $(0,1)$ and $(1,0)$ modes, $\pi/2$ out of phase [note the $(1,1)$ mode was omitted since this destroys the doughnut nature of the beam in a coherent superposition]. The spectrum in this case shows that a statistical correlation exists in every direction.

In conclusion we have introduced an experimental system capable of generating structured partially coherent beams whose spatial coherence can be tailored by the user. By way of demonstration, a partially coherent doughnut beam was generated. Additionally, the spatial degree of coherence of the generated beam was determined at specific locations by measurement of the Fourier spectrum produced by a 2D nonredundant array of pinholes. The interpretation of the data proved simpler and more informative when using the Fourier spectrum, since it represents the degree of spatial coherence as a function of the separation and orientation of the pinhole pairs.

The availability of a setup with these capabilities enables one to study partial coherence to a better extent. It is possible to study, for example, the propagation of partially coherent light through high numerical aperture systems [15] or the effect of coherence in nonlinear media at nanoscopic scales.

This work was supported by the EU research grant Super Resolution Photonics for Advance Storage Systems (SURPASS) 224226, and Consejo Nacional de Ciencia y Tecnología (CONACyT). The experimental work presented constituted part of R. Lim's master's in a research project conducted at Imperial College London.

### References

1. R. N. Zare, Science **279**, 1875 (1998).
2. M. Shapiro and P. Brumer, Phys. Rev. Lett. **77**, 2574 (1996).
3. V. V. Dantus and M. Lozovoy, Chem. Rev. **104**, 1813 (2004).
4. M. S. Zubairy and J. K. McIver, Phys. Rev. A **36**, 202 (1987).
5. J. H. Churnsidea, Opt. Commun. **51**, 207 (1984).
6. Y. Cai and U. Peschel, Opt. Express **15**, 15480 (2007).
7. M. J. Pu and T. Wang, Appl. Opt. **45**, 7553 (2006).
8. W. N. Partlo and W. G. Oldham, J. Vac. Sci. Technol. B **9**, 3126 (1991).
9. H. Nakano, N. Miyanaga, K. Yagi, K. Tsubakimoto, T. Kanabe, and M. Nakatsuka, Appl. Phys. Lett. **63**, 580 (1993).
10. P. D. Santis, F. Gori, G. Guattari, and C. Palma, J. Opt. Soc. Am. A **3**, 1258 (1986).
11. A. I. González and Y. Mejía, AIP Conf. Proc. **992**, 478 (2008).
12. J. W. Goodman, *Statistical Optics* (Wiley, 2004).
13. E. Wolf, Opt. Commun. **38**, 3 (1981).
14. W. Neil and Juškaitis, J. Microsc. **197**, 219 (2000).
15. M. R. Foreman and P. Török, J. Opt. Soc. Am. A **26**, 2470 (2009).