Spatial information transmission using orthogonal mutual coherence coding

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We use the coherence of a light beam to encode spatial information. We apply this principle to obtain spatial superresolution in a limited aperture system. The method is based on shaping the mutual intensity function of the illumination beam in a set of orthogonal distributions, each one carrying the information for a different frequency bandpass or spatial region of the input object. The coherence coding is analogous to time multiplexing but with multiplexing time slots that are given by the coherence time of the illumination beam. Most images are static during times much longer than this coherence time, and thus the increase of resolution in our system is obtained without any noticeable cost. © 2005 Optical Society of America

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The aim of the approach presented in this Letter is to use coherence coding to exceed the diffraction limit of resolution forced by the physical dimensions of an imaging lens. The suggested concept is as follows: an optical setup produces a light beam with the desired mutual intensity function (MIF). This beam illuminates the input object. The illumination is such that every spatial region in the input object has orthogonal MIF coding such that after mixing all those regions and sending them through an aperture-limited imaging system, the information is not lost. After transmission through the space-limited imaging system the image is recovered using an optical decoding system that is identical to the coding system. In decoding, the spatial information is separated using the orthogonality property of the various MIFs that coded the object. The decoding recovers the information after time averaging. However, since the temporal fluctuations of the phases are at the speed of light, the averaging time should be a few times the illumination coherence time (which could be as low as femtoseconds). For orthogonal coding the capability of synthesizing a desired MIF function is required. Such a capability may be obtained using iterative algorithms in which incoherent light is propagated through free space and multiplied by spatial masks.[1,2] One example of orthogonal MIF coding is depicted in Fig. 1, in which three orthogonal MIF distributions are presented (each MIF has a line that is positioned at a different distance from the central diagonal) and may be used to code three different spatial regions of the object. Note that the MIF may be displayed and processed optically.[3–5]

The definition of MIF is[6–8]

$$\Gamma(x_1,x_2) = \langle u(x_1,t)\, u^*(x_2,t)\rangle, \tag{1}$$

where $u(x,t)$ is the input complex amplitude, x_1 and x_2 are spatial coordinates, and t is the time axis. $\langle\ \rangle$ describes ensemble averaging over time. For simplicity we assume one-dimensional (1-D) objects. Following the previous example, shown in Fig. 1, the three orthogonal functions are as follows:

$$\Gamma_n(x_1,x_2) = [\,\delta(x_1 - x_2) + \delta(x_1 - x_2 - n\alpha) + \delta(x_1 - x_2 + n\alpha)]\mathrm{rect}(x_1/\Delta x)\mathrm{rect}(x_2/\Delta x), \tag{2}$$

where $n = 1$, 2, 3 and α is a constant. Δx describes the spatial dimensions of the object. As shown in Fig. 1, each MIF is constructed out of three lines, while the central line we will call the zero-order line, and the upper and the lower lines will be called the 1st- and the −1-order lines, respectively. Orthogonality is obtained due to the fact that the three MIFs do not coincide, since each line has a different shift (due to different n). The three distributions in the example are obtained using the numerical recipe described in Ref. 1 based on iterative computation of a spatial phase

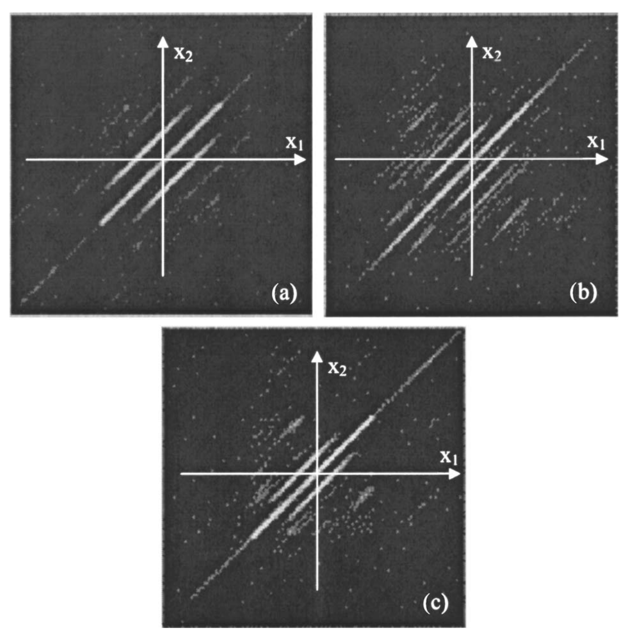

Fig. 1. Examples of three orthogonal MIFs.

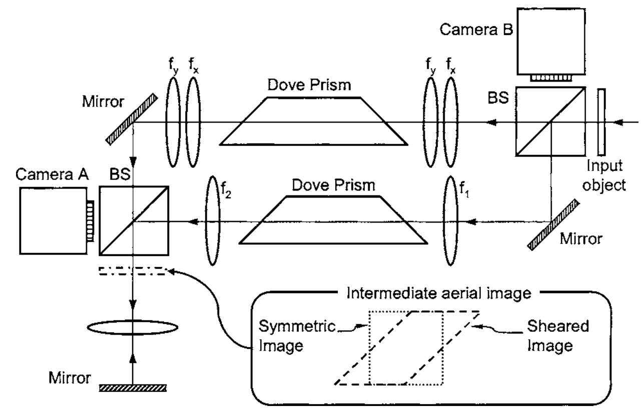

Fig. 2. Schematic of the optical configuration. BS, beam splitter.

only mask such that after free-space propagation the desired MIF distribution is realized. Nonetheless, the MIF distribution can be generated by various other methods. In the experiments shown in this Letter, the MIF is generated by the method described below.

The effect of a spatial transformation on the complex amplitude impinging on an optical system can be described, for a linear system, as

$$u_t(x) = \int u(x_1)B(x_1,x)\mathrm{d}x_1, \qquad (3)$$

where $u_{\mathrm{t}}(x)$ is the complex amplitude after the transformation and $B(x_1,x)$ is the transformation kernel. Kernel $B(x_1,x)$ can be any function describing an optical system, such as a free-space propagator, imaging kernel, or Fourier transform kernel. Analogously to Eq. (1), the MIF of the output distribution of the system, $\Gamma_t(x_1,x_2)$, can be calculated[7] as

$$\Gamma_t(x_1,x_2) = \langle u_t(x_1,t)u_t^*(\mathrm{x}_2,\mathrm{t})\rangle = \iint \langle u(\bar{x}_1,t)u^*(\bar{x}_2,t)\rangle B(\bar{x}_1,x_1)B^*(\bar{x}_1,x_2)\mathrm{d}\bar{x}_1\mathrm{d}\bar{x}_2, \qquad (4)$$

which results in

$$\Gamma_t(x_1,x_2) = \iint \Gamma(\bar{x}_1,\bar{x}_2)B(\bar{x}_1,x_1)B^*(\bar{x}_1,x_2)\mathrm{d}\bar{x}_1\mathrm{d}\bar{x}_2. \qquad (5)$$

Making use of Eq. (5), it is possible to tailor the MIF, as one can modify the transformation kernel by properly designing the optical system. For instance, diffractive optical elements may be used to obtain any arbitrary impulse response. As a result, virtually any physically meaningful MIF can be synthesized.

For demonstration of our principle we constructed the setup depicted in Fig. 2, which demonstrates one-dimensional (1-D) superresolution by coherence coding. The setup consists of two optical paths that will generate a double image of the input plane. One will be a regular image and the other a sheared image. In the first path (the top one) we constructed an anamorphic imaging system containing two imaging lenses in the vertical axis (with focal lengths f_y) and two different focal length (f_x) lenses in the horizontal axes. This configuration provides a different magnification for the two directions. The second optical path (the bottom one) includes regular spherical imaging realized using two lenses (with focal lengths f_1 and f_2). In addition, a Dove prism is introduced into the intermediate space of each of the two systems to provide a tunable rotation between the images given by both systems. Both paths were combined using beam splitters, providing an aerial intermediate double image (at the location indicated by the inset in Fig. 2). The interference between the image and its sheared version allows MIF coding. After proper alignment, the described configuration allows us to realize a situation in which every 1-D row of the image is added to the same row with a different shift (see the inset of Fig. 2). Since each row has a different shift, orthogonality is obtained in the coding process. The fact that a certain row is added to a certain given shift of that row is equivalent to having a MIF with a different shift between the zero and the 1st- and (or) −1-order lines, i.e., different n coefficient in Eq. (2) (see Fig. 1). Camera A is located at the plane where both paths are recombined and is used only for proper alignment of the system. A mirror and a lens are placed there, while a slit attached to the mirror plane is placed to simulate an imaging system with a limited aperture in one direction. This aperture reduces the spatial resolution that passes through the overall optical configuration. After the mirror the image is backreflected and passed through the same system again. The second back passage through the system performs the decoding of the information. The output is sensed by camera B. The superresolved image at the plane of camera B could be obtained after very short temporal averaging of a few femtoseconds. In the actual experiment both cameras (with resolution 640×480 pixels and pixel size of $7\ \mu\mathrm{m}\times7\ \mu\mathrm{m}$) operate at video rate.

The experimental results of the constructed system are presented in Fig. 3. The image seen at the output plane (camera B) is shown in Fig. 3(a). The informa-

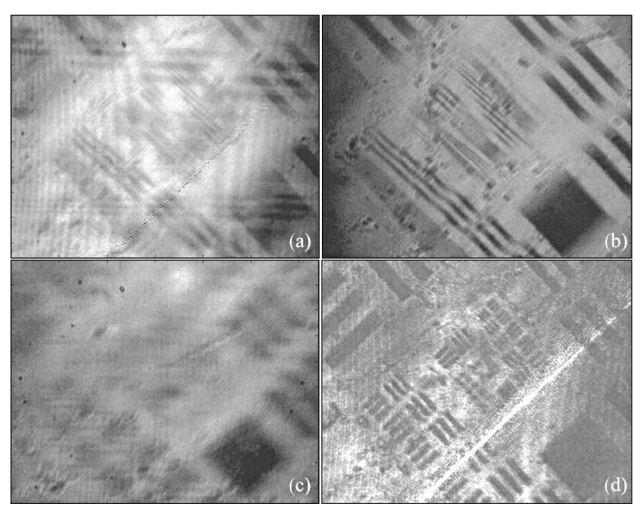

Fig. 3. (a). Overall optical output of the system showing the interference between both paths. (b) Output of the anamorphic optical path. (c) Output of the spherical optical path. (d) Superresolved image obtained after applying the proposed method.

tion carried by the coherence coding is contained in the interferences. The individual output image seen in each optical path is displayed in Figs. 3(b) and 3(c). Those images were obtained simply by blocking one of the optical paths and observing the light imaged at the nonblocked path. In Fig. 3(d) one may see the superresolved image obtained after removing the incoherent image contributed by the system. Since the slit at the aperture plane was 1-D, the image in Fig. 3(a) was blurred in one dimension and the features were lost along that direction. Comparing Fig. 3(d) with Fig. 3(a), one may see the significant improvement that was obtained. Features that were completely blurred at the center of the image were fully recovered after applying the described superresolving approach.

In summary, we have presented a novel approach for coding spatial information using the mutual intensity function, and we have demonstrated the principle by improving the resolution of an aperture-limited optical imaging system. The coherence coding that we have presented is, to a given extent, equivalent to time multiplexing. However, the multiplexing encoding time slots are given by the coherence time of the light source and can be as low as femtoseconds. Thus the temporal bandwidth of the image is much smaller than the temporal bandwidth of the light and the increase in spatial resolution in our method is obtained at no noticeable cost.

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