Spatial information transmission using axial temporal coherence coding

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We present an approach that can be used for transmission of information through space-limited systems or for superresolution. The spatial information is coded with different axial temporal coherence by interfering every spatial region in the input with the same region, but with a certain known delay in the longitudinal axis. Every spatial region has different delay. After mixing all of the spatial information, it is transmitted through the space-limited system. At the detection the information is passed through a similar interference setup containing certain axial delay. By temporally scanning along the longitudinal axis, each time a different spatial region that was coded with the corresponding axial delay is reconstructed. To allow coding of different spatial regions with different and small axial delays, we use a thermal light source that has very short coherence length. We include experimental validation of the presented approach. © 2007 Optical Society of America

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The Rayleigh diffraction limit gives the maximum density of spatial information that can be transmitted through an optical system. Together with the field of view, it defines the space-bandwidth product of the system that determines the amount of information that can be handled by a system.[1] Nevertheless, this limit can be circumvented by coding additional information on unused degrees of freedom of the system. A typical application of this concept is in superresolution, whose aim is to pass the spatially high-resolution information throughout a space-limited system. It can be achieved by producing a synthetically large aperture by coding the spatial features into different domains such as time, polarization, or wavelength.[2–8] It is worth noting that the information capacity increase is the relevant issue in superresolution application and can alternatively be achieved by a field-of-view increase keeping the system resolution constant. This corresponds to an exchange between spatial and spatial-frequencies spaces. Field of view and resolution (as given by the cutoff frequency of the system) are dual quantities in these spaces.[3]

Recently a new technique that uses orthogonal mutual coherence coding was proposed.[9] This technique is based on illuminating the object with orthogonal coding of the mutual intensity function (MIF). By using the fact that the MIF can be synthesized, displayed, and optically processed,[9–13] an optical coding system that overcomes the diffraction limit was demonstrated. Based on the fact that spatial information coding can be implemented using orthogonal mutual coherence coding, we suggest an alternative approach of using temporal coherence coding, i.e., instead of generating a transversally different coherence distribution, we use the longitudinal axis to code the transversal spatial information. By applying different axial coherence to different spatial pixels of the object, we can fold a two-dimensional image into a smaller spatial domain (a single pixel, in the limit case) and then transmit it through the space-limited system. The decoding setup will be similar to the encoding one.

The suggested concept is as follows: an optical setup produces a light beam with the desired self-coherence function (SCF). This beam illuminates the input object. The illuminating beam consists of a sum of a reference beam and the same beam passed through a spatial mask having different time delays in different spatial regions. The illumination is orthogonal; i.e., there are no two spatial regions having the same time delay. After transmitting the coded information through the space-limited imaging system, the image is recovered using an optical decoding system that is identical to the coding one. In the decoding, the multiplexed spatial information is separated and the image is reconstructed by separating the various SCFs that coded the spatial content of 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 can be as short as a few times the illumination coherence time (which could be as low as femtoseconds).

The SCF is defined as described in Ref. 14:

$$|\Gamma_{11}(\tau)| = \langle u(P,t+\tau)u^*(P,t)\rangle, \tag{1}$$

where $u(P,t)$ is an input complex amplitude, P represents the spatial coordinates, t is the time axis, and τ

is the time difference between the points. $\langle\,\rangle$ describes ensemble averaging over time. For an incoherent field $|\Gamma_{11}(\tau)|=0$ for all $\tau\neq 0$. The coding system is based on the possibility that every spatial region can have autocorrelation with a unique time delay that will separate this specific spatial region from the others. The recovery of every region will be based on the time delay that was used for its coding. The incoherent light used in the coding system can be described by the temporal phase decorrelation after a time that is longer than the coherence time τ_c. The coherence time has a value that is of the same order of magnitude as $1/\Delta v$, where Δv is the spectral bandwidth of the illuminating source. We use broadband spectrum illumination to have short τ_c. Proper coding will generate a SCF $|\Gamma_{11}(\tau(P))|=\langle u(P_1,t+\tau(P))u^*(P_1,t)\rangle$ that in the decoding will yield $|\Gamma_{11}(\tau(P))|=0$ for all $\tau(P)$, except when $\tau(P)=\tau(P_1)$, where it has a finite value.

In the experimental validation, we demonstrate a reduction in the spatial extent to be transmitted by the system, by the use of the proposed coherence coding, by a factor of 2. We have constructed the experimental schematic setup as depicted in Fig. 1(a). The picture of the encoding part is seen in Fig. 1(b). The complete setup consists of two Michelson interferometers, one for the coding and the second for decoding. After the coding and before the decoding, we have spatial compression of the information to simulate its transmission through a space-limited system, such as a conventional imaging system or a fiber bundle.

The first interferometer was built from two branches with the same length. One branch has an addition of thin glass that time shifts half of the image by τ_c from the second half. A thicker glass holds the delay plate, and a similar one is used in the other branch for compensation [Fig. 1(b)]. Afterward the image is compressed, superimposing the two halves of the image, one on top of the other. The second interferometer (the decoding part) is made initially with two equal length branches, where in one of the branches the length can be varied. The length variation controls the time delay τ_{c_3}, enabling us to recover the specific region with the same time coding. Mathematically, assuming the time delay of the τ_{c_1} coded image of spatial region P_1 and the τ_{c_2} coded spatial region of P_2, when we tune the decoding setup for the proper time delay of τ_{c_1} or τ_{c_2}, we have extracted the corresponding spatial region:

$$\begin{aligned}|\Gamma_{11}(\tau_{c_1})| &= \langle[u(P_1,t)+u(P_2,t)][u(P_1,t+\tau_{c_1}) \\ &\quad + u(P_2,t+\tau_{c_1})]^*\rangle \\ &= \langle u(P_1,t)u^*(P_1,t+\tau_{c_1})\rangle, \\ |\Gamma_{11}(\tau_{c_2})| &= \langle[u(P_1,t)+u(P_2,t)][u(P_1,t+\tau_{c_2}) \\ &\quad + u(P_2,t+\tau_{c_2})]^*\rangle \\ &= \langle u(P_2,t)u^*(P_2,t+\tau_{c_2})\rangle. \qquad (2)\end{aligned}$$

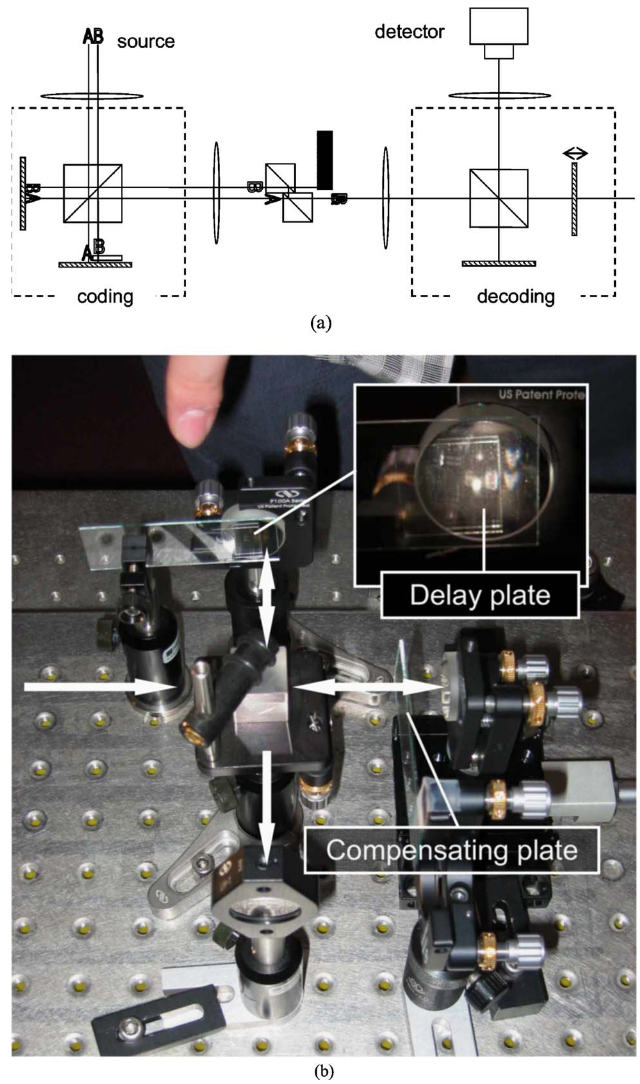

Fig. 1. (Color online) (a) Schematic of the setup. (b) Encoding part of the setup showing the delay plate.

In the experiment, we used two illuminations sources: one of white light (with a halogen lamp) and the other was the same light after being filtered by a green inteferential filter. The SCF is seen as fringes in the captured images, featuring various colors for the white light source, shaded black and green for the green light source. In the experiment, the image was divided in two; one half consisted of the letter A and the second half with the letter B, both recorded on a photographic transparency. In the first interferometer, the double image was coded, so A had a time delay of τ_c and B had $2\tau_c$. The output of the encoding system can be adjusted according to three cases:

1. When the difference between the branches corresponded to τ_c, B was not affected from the SCF and was static, and A had fringes [Fig. 2(a) for white light and Fig. 2(c) for green].
2. When the difference between the branches corresponded to $2\tau_c$, A was static and B had the fringes [Fig. 2(b) for white light and Fig. 2(d) for green].
3. When the difference between the optical paths was null, both A and B had fringes.

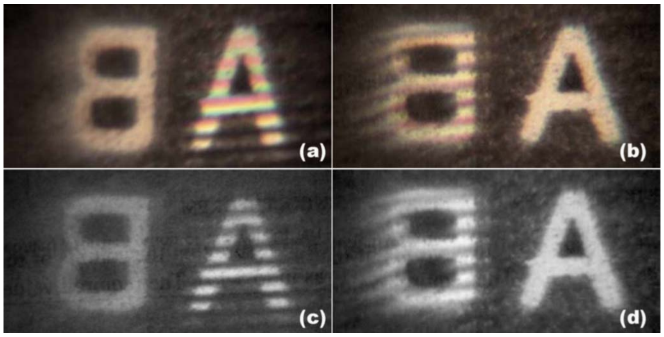

Fig. 2. (Color online) Output of the encoding system without using the mixing system. It can be adjusted to show interferences in white light for the (a) A pattern or in the (b) B pattern by adjusting the paths in the interferometer. The contrast is enhanced with a narrowband interference filter [(c) and (d) for patterns A and B, respectively].

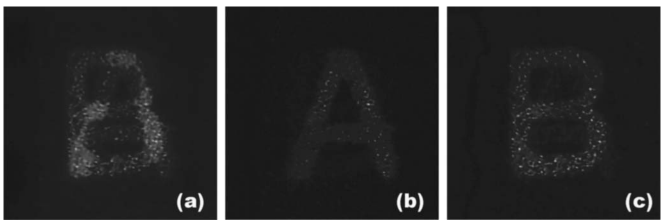

Fig. 3. (a) Output of the system for an arbitrary path difference in the decoding interferometer. (b) Visibility extracted when the path difference is varied around the value for the A pattern. (c) Visibility extracted when the path difference is varied around the value for the B pattern. The results are obtained for green illumination.

After the spatial compression, A was superimposed on B. Decoding by SCF is implemented in the second interferometer. Both systems were implemented using simple lenses (singlets), which provide enough resolution and field of view for the target with the double spatial content. In a real application, this stage precedes the system whose bandwidth is to be enhanced, and higher-quality lenses with chromatic correction should be used as required by the spatial resolution of the system. The dephasing mask is used for decomposing the field of view in regions with different axial coherence. Thus the resolution requirements are not large. For instance, a 5×5 mask would multiply the information capacity by a factor of 25 with a mask with sections that are still over millimeter size, not compromising the resolution of the encoding system. The superimposing system in this case should be more complex than the one we have used. A combination system can be arranged by means of a multifaceted element or by diffraction gratings.

In Fig. 3, one may see the decoding results obtained for the green light. In Fig. 3(a), one may see the output of the system for an arbitrary path difference in the decoding interferometer. In Fig. 3(b), one may see the visibility extracted when the path difference is varied around the value for the A pattern. In Fig. 3(c), one may see the visibility extracted when the path difference is varied around the value for the B pattern. It is worth noting that the use of a narrowband filter, combined with the visibility extraction, has removed to a large extent the noise of the image, removing the light that does not fulfill the coherence requirements. This brings an image with higher visible resolution displaying even the film grain. Note also that the different regions of the object are decoded in the time sequence. Thus the field of view of the second system can be the same as that of the transmitted information.

The magnitudes of the time delays are chosen so that

$$\tau_c = \frac{2L_c(n-1)}{c}, \qquad (3)$$

where L_c is the width of the glass that was used in order to generate the difference in the optical paths (the factor 2 appears since in the Michelson configuration the light passes twice through the glass), n is the index of refraction, and c is the speed of light. In the experiment, n was 1.525 and L_c was 0.15 mm, so we get $\tau_c = 5.25\times 10^{-13}$ s. This is compatible with a bandwidth of 1.9 THz. The green filter had a wavelength of 532 nm with a bandwidth of 10 nm (10.6 THz bandwidth, indeed larger than 1.9 THz). In the experiment with the white light source, the spectral bandwidth is even larger.

It is worth noting that although the experiment has been performed with a transilluminated object, it can be also made with diffuse objects under natural lighting conditions, as no restriction is needed on the illumination. This fact opens the possibility of using the approach for real world scenes.

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