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Super-resolved or field of view enlarged imaging based upon spatial depolarization of light

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ABSTRACT

In this paper we present a new approach allowing the surpassing of the diffraction based limitation for the achievable resolution provided by imaging systems. It is based on an encoding–decoding process of various spatial pixels or regions in the field of view of the imaged object by orthogonal and differently time varying polarization states.

The reconstruction of the original spatial information is obtained by applying a decoding process in a way similar to the encoding one. Although all the spatial information is summed and mixed together by the system, the decoding provides super-resolved imaging since in every spatial position the undesired spatial information having time varying polarization dependence, that is uncorrelated to the decoding sequence applied on that specific spatial position, is averaged to zero and, on the other hand, the information which corresponds to that specific spatial region is being reinforced.

The proposed approach can be used not only for super-resolved imaging but also for imaging module that maintains the same spatial resolution while providing enlarged field of view.

1. Introduction

Super resolution [1,2] is the field in which coding spatial degrees of freedom by other domains as time [3,4], wavelength [5–8], code or field of view [9,10], grey levels [11], coherence [12,13] and polarization [14,15] allows overcoming resolution limits of imaging systems posed by the diffraction effect. The spatial information is encoded by one of the other domains and after being transmitted through the imaging system it is decoded to reconstruct the high resolution image.

In recent work the coherence property of light was used to increase resolution or to obtain the same resolution over larger field of view [12,13]. The idea included synthesizing the mutual coherence of the illumination source and then multiplexing the spatial information while using this apriori known encoding illumination, transferring the information through the imaging system and eventually demultiplexing it and reconstructing the high resolution image. At first the encoding was done by shaping the transversal coherence distribution and using it to improve the lateral resolution [12] and later on by the axial coherence [13] where the authors presented how to preserve the same resolution over an increased field of view.

In this paper we follow the line presented in Ref. [13] while the capability for increasing the field of view is obtained not by encoding each region in the field of view by different axial delays (while each is larger than the coherence distance of the illumination source), but rather by proper source depolarization.

In the proposed concept the illumination source is depolarized in such a way that various spatial regions of the field of view are illuminated by differently time varying polarization states. The depolarization is such that the polarization variations in the different regions of the illumination spot are orthogonal to each other and thus time averaging may allow separating the various parts of the illumination spot (that coded different regions of the field of view) even if they were summed together. As in the case of field of view coding by the axial coherence of the illumination, here as well the time averaging duration that is required in order to orthogonally separate the multiplexed lateral regions is very short (since on one hand the polarization can be changed quickly and on the other hand the encoding/decoding is done in parallel, rather than in serial, to all spatial regions simultaneously).

Note that in contrast to polarization related super resolving approach presented in Ref. [15] here we do not seek to obtain the reconstruction by matrix inversion but rather just by time averaging of the properly decoded depolarization of the encoded illumination source.

The theory is presented in Section 2 while in Section 3 we present numerical and experimental validation of the proposed approach. The paper is concluded in Section 4.

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2. Theoretical description

We assume that the illumination source is depolarized such that various spatial regions within the illumination spot have different and orthogonal time varying states of polarization. We denote by $P(x,t)$ the spatial distribution of the temporal variation of the polarization state in the illumination spot.

We assume that the input object, which is denoted by $g_{\text{in}}(x)$, is illuminated by the time varying polarization:

$$g_{\text{in}}(x) = \sum_n g_{\text{in}}^{(n)}(x - n\Delta x) \tag{1}$$

where Δx is the size of the lateral regions that we aim to multiplex and $g_{\text{in}}^{(n)}$ is the spatial distribution of the input object in those lateral regions.

After illuminating the input object with the depolarized source one has:

$$g_{\text{in}}^{(p)}(x) = \sum_n P(x,t) g_{\text{in}}^{(n)}(x - n\Delta x) \tag{2}$$

Right after the various lateral regions are being multiplexed together and passed through laterally narrow region of regard, Δx:

$$\begin{aligned} g_{\text{multiplex}}(x) &= \text{rect}\left(\frac{x}{\Delta x}\right) \times \sum_n g_{\text{in}}^{(p)}(x - n\Delta x) \\ &= \sum_n g_{\text{in}}^{(n)}(x) P(x - n\Delta x, t) \end{aligned} \tag{3}$$

the demultiplexing process involving extracting the original wide field of view information by replicating the transmitted spatially multiplexed distribution and interfering it with the same depolarized source.

Alternatively, the decoding may also be obtained by passing the transmitted illumination through space and time varying polarizer having spatial–temporal distribution identical to the illumination source $P(x,t)$. The lateral replication using Eq. (3) gives:

$$\sum_n g_{\text{multiplex}}(x - n\Delta x) = \sum_n \sum_m g_{\text{in}}^{(n)}(x - m\Delta x) P(x - (n-m)\Delta x, t) \tag{4}$$

then the decoding which involves multiplication by $P(x,t)$ and time averaging yields:

$$\begin{aligned} g_{\text{rec}}(x) &= \int \sum_n g_{\text{multiplex}}(x - n\Delta x) P(x,t) dt \\ &= \int \sum_n \sum_m g_{\text{in}}^{(n)}(x - m\Delta x) P(x - (n-m)\Delta x, t) P(x,t) dt \\ &= \sum_n \sum_m g_{\text{in}}^{(n)}(x - m\Delta x) \times \int P(x - (n-m)\Delta x, t) P(x,t) dt \end{aligned} \tag{5}$$

Due to the orthogonality property (this is for the correlation part only, in addition there is a DC component that should be subtracted) one has:

$$\int P(x - (n-m)\Delta x, t) P(x,t) dt = \delta[n-m] + \text{const} \tag{6}$$

where $[n\text{-}m]$ is a delta function equals one when $n = m$ and zero otherwise. The constant DC level will be subtracted from the reconstructed image and thus the relevant part of the reconstruction equals to:

$$g_{\text{rec}}(x) = \sum_n \sum_m g_{\text{in}}^{(n)}(x - m\Delta x) \delta[n-m] = \sum_n g_{\text{in}}^{(n)}(x - n\Delta x) = g_{in}(x) \tag{7}$$

Thus, reconstruction of the original high resolution object over the full field of view is obtained.

Note that the ability to achieve the orthogonality property in practice, using a polarizer, is done by randomly changing the polarizer's direction so that the undesired components will behave as unpolarized light and by the subtraction of the background level we will remain only with the desired orthogonal part.

3. Numerical and experimental validation

In the first step we constructed a numerical simulation in which we aim to demonstrate the usage of the proposed approach for super-resolved imaging. In our first demonstration that is presented in Fig. 1, the idea is to encode a 2-D image into a single pixel value and to transmit it through resolution limiting system and eventually to reconstruct the original object.

Our object in the simulation was an image of 16 by 16 pixels that is presented in Fig. 1a. It was encoded using the proposed approach. Each one of the 16 by 16 pixels was encoded with different time varying orthogonal polarization sequence, that was random and independent of its neighbours. Then, all the pixels were added (i.e. mixed) into a single pixel value. This imitates the low resolution system having the resolution limitation we aim to overcome. Then, the one value was replicated 16 by 16 times and for each one of the replications proper time varying polarization sequence was applied.

Note that the fact that the polarization states of each pixel are completely "independent" of its neighbours can be achieved in practice by using a mask build from many linear polarizers where every region has an independent direction. It may also be obtained with a spatial light modulator (SLM) that will add to every pixel a different change in its polarization state.

The reconstruction after DC subtraction is presented in Fig. 1b. To obtain the presented result we did 100,000 averages, i.e. we used 100,000 different polarization states in our depolarization sequence and summing them after DC subtraction. One may see that indeed the reconstruction is very similar to the original object.

Note that the processing was performed in the following way: First we found the DC value by taking a low-resolution image without using any encoding mask. This value had been subtracting from every result obtained during the decoding. Then, we summed all the results, and finally normalized it linearly so that the resulted values will be between 0 and 1.

In the next simulation of Fig. 2 we aimed to demonstrate super-resolved imaging by transmitting low-resolution image and then recovering its original resolution by applying the polarization based proposed approach. In Fig. 2a one may see the original binary high resolution image which was blurred with 3 by 3 blurring kernel such that the image of Fig. 2b was obtained. This image was transmitted. The blurring kernel that we used was: $\begin{bmatrix} 1/16 & 1/8 & 1/16 \\ 1/8 & 1/4 & 1/8 \\ 1/16 & 1/8 & 1/16 \end{bmatrix}$.

The obtained reconstruction after applying 140 averages (i.e. we used 140 different polarization states in our depolarization sequence) is seen in Fig. 2c. We obtain a reconstruction which is identical to the original high resolution image.

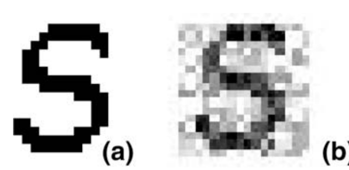

Fig. 1. Numerical simulation for reconstruction after transmitting the 2-D object as a single pixel value. (a) The original object. (b) The obtained reconstruction.

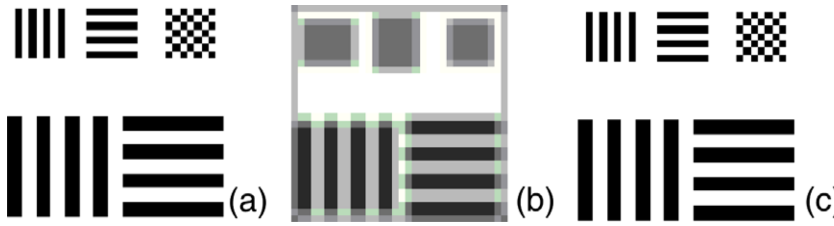

Fig. 2. Numerical simulation for reconstruction an image blurred by 3 by 3 pixels kernel. (a) The original object. (b) The low resolution transmitted 2-D information. (c) The obtained reconstruction.

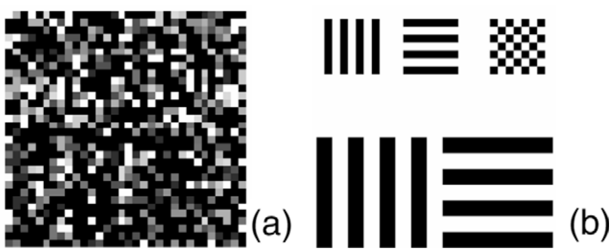

Fig. 3. The effect of noise. (a) The blurred image of Fig. 2b after the addition of zero mean white Gaussian noise with two sigma equal to 1. (b) The obtained reconstruction.

In Fig. 3 we investigate the effect of noise on the reconstruction capability of the proposed polarization multiplexing approach. The original binary image of Fig. 2a was blurred with the 3 by 3 kernel to obtain the image of Fig. 2b. To this image a zero mean white Gaussian noise with two sigma equal to 1 was added. This resulted with the image of Fig. 3a. After applying the proposed reconstruction we obtained the image of Fig. 3b which is identical to the high resolution image of Fig. 2a. Thus, it is clear that the proposed approach is very immune against additive noise. This is basically understandable since in the simulation of Fig. 1 we also summed all the pixels of the image together and yet were able to reconstruct the original high resolution object (all the undesired pixels when added to a given inspected pixel are basically an additive cross talk noise).

The next step is to obtain optical experimental validation. The experimental setup may be seen in Fig. 4. At our first experiment the intension was to multiplex two regions of the field of view, to transmit them through the imaging system and then being able to decode and to demultiplex the two regions and to construct the original image of the full field. Experimentally we did not present a resolution improvement but it can be achieved with a setup that will use an SLM based encoding or a mask that will differently polarize each spatial region.

In Fig. 4 we imitate the depolarization of the illumination source by using time varying polarizers. Two images were multiplexed. Polarizer 1 is a fixed polarizer and polarizers 2 and 3 are randomly varied in time with possibility to control for each its own random sequence. Polarizers 1 and 2 were the encoding polarizers and polarizer 3 was used to decode the two multiplexed images (coming from two lateral regions in the field of view). The mixing of the two images was done using a beam splitter (denoted in the figure as B.S.).

The obtained results are seen in Fig. 5. In Fig. 5a we reconstructed image 1 (originally coming from branch 1). In Fig. 5b we repeated the same experiment when image 1 is attenuated 5 times more than the undesired image 2. This is to show that the orthogonal depolarization sequence allows reconstruction even when the required spatial information is lower in its signal to noise ratio in comparison to the undesired information (regarded as noise). In Fig. 5c we reconstructed image 2. In all cases one may see the reconstruction of the original images as appearing in the sketch of Fig. 4.

In order to do this reconstruction we applied a sequence of 36 time averaged frames (36 different polarization states in our time varying sequence) each having different polarization state.

Note that the recovery time, i.e. the number of summed images, depends on several factors: the number of pixels in the spatial compression, the image structure and the noise level in the system. The number of pixels in the spatial compression determines the amount of background noise per pixel, more pixels provide more noise. The image structure is related to the amount of its spatially high frequencies.

Using the 36 images in the averaging operation of the experimental part did not intend to show the minimal number of terms required for the summation. The purpose was to demonstrate the random distribution of the polarization states since for small num-

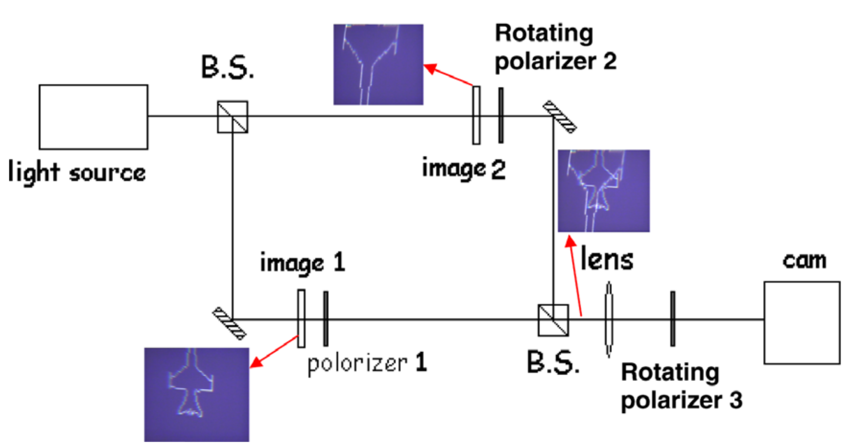

Fig. 4. The experimental setup with two regions coding.

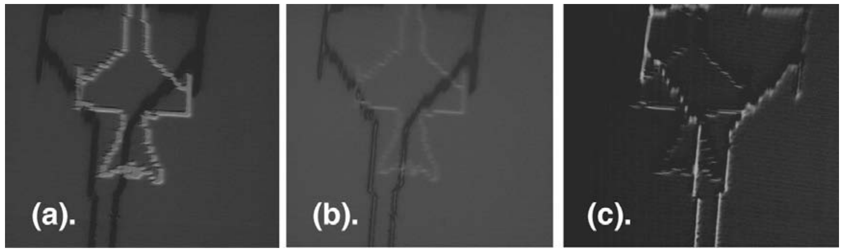

Fig. 5. Experimental results. (a) Reconstruction of image from branch 1. (b) Reconstruction of image from branch 1 even when it is 5 times more attenuated than the original image of branch 2. (c) Reconstruction of image from branch 2.

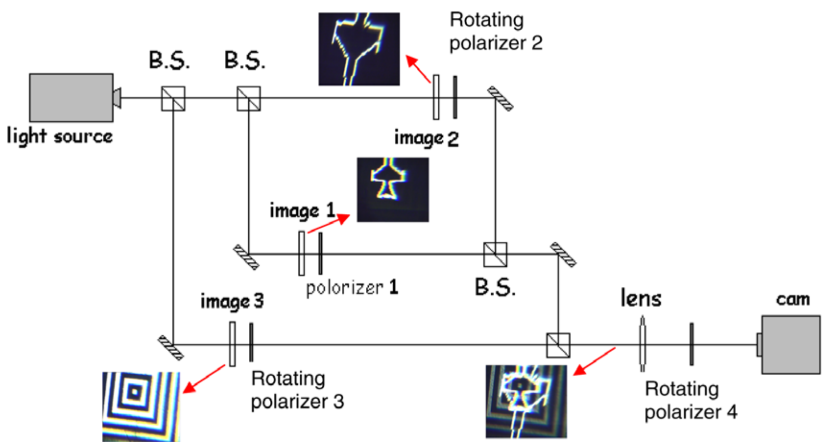

Fig. 6. The experimental setup with three regions coding.

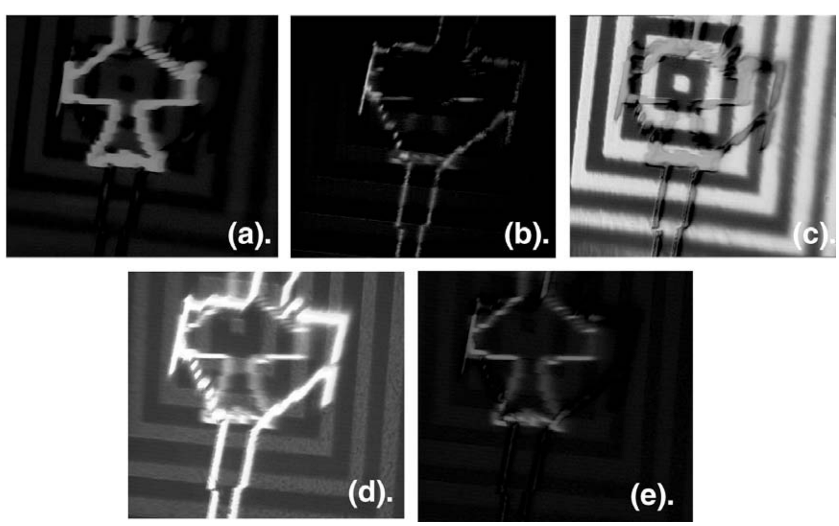

Fig. 7. Experimental results. (a) Reconstruction of image from branch 1. (b) Reconstruction of image from branch 2. (c) Reconstruction of image from branch 3. (d) The case when the input image from branch 2 is four times stronger than the rest of the images. (e) The reconstruction of image from branch 1 for in the input case of Fig. 7(d).

ber of samples it is difficult to exhibit sufficiently random distribution. In that specific experiment the number of regions that can be resolved is greater than three (which was demonstrated). The real purpose of the experiment was to show the ability to restore the image even though there is a strong background level (and indeed we were able to recover the image even though the other branches, which are considered as noise to be filtered out, had more intensity than the inspected image).

Note also that the results presented in Fig. 5 aimed to show only the preliminary validation of the proposed approach and thus they were obtained without any image processing algorithmic which might have improved the reconstruction quality even further.

In Fig. 6 we upgraded the setup of Fig. 4 to encoding/decoding of three rather than two spatial regions. In this case encoding polarizer 1 was fixed and polarizers 2 and 3 were rotating. The decoding polarizer 4 was rotating as well. Each rotating polarizer was shifted between 6 angular positions (each at angular difference of 30 degrees). Thus, for the encoding there were 36 (=6 $\times$ 6) different polarization states. The obtained preliminary results, after averaging all captured images, while applying in the decoding polarizer (polarizer 4) the required decoding sequence, are seen in Fig. 7.

One may see that all three multiplexed images (coming from three different spatial regions) were separated from each other. In Fig. 7a–c we present the capability of separating the multiplexed objects of region 1, 2 and 3 respectively. In Fig. 7d we repeat the same experiment when the image of region 2 is amplified 4 times more than the images of the rest of the regions while we try to reconstruct image from region 1 (the result of the reconstruction for the input of Fig. 7d is seen in Fig. 7e). One may see that although the image from region 1 was attenuated more than the image from region 2, we yet could reconstruct it. This experiment shows that the orthogonal depolarization sequence allows reconstruction even when the required spatial information is lower in its signal to noise ratio in comparison to the undesired information (regarded as noise).

4. Conclusions

In this paper we have demonstrated a super resolving and a field of view multiplexing approach in which various lateral regions of the field of view are encoded by synthesizing the depolarization of the illumination source. By interfering the output with the encoding source or by time varying polarizers following the same depolarization sequence, allows to separate the multiplexed regions of the field of view and to reconstruct the original high resolution image.

Although experimentally demonstrated for field of view multiplexing (i.e. having larger field of view with the same resolution), one may use the same approach for resolution improvement configuration where each spatial pixel that we aim to transmit will be encoded by orthogonal time varying polarization sequence (as demonstrated by the numerical simulation).

The proposed approach was numerically and experimentally validated and showed good reconstruction capabilities even when the lateral region to be extracted has lower signal to noise ratio in comparison to the other undesired lateral regions.

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