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Discussion

Optical super resolution using tilted illumination coupled with object rotation

Anwar Hussain [a,*], Asloob A. Mudassar [b]

[a] COMSATS Institute of Information Technology, Park road, Chak Shahzad, Islamabad, Pakistan
[b] Department of Physics and Applied Mathematics, Pakistan Institute of Engineering and Applied Sciences, Islamabad 45650, Pakistan

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ABSTRACT

In conventional imaging systems, the resolution of the final image is mainly distorted due to diffraction of higher spatial frequencies of the target object. To overcome the diffraction limit, imaging techniques which synthetically enlarge the aperture of the system are used. In this paper, synthesized aperture is produced by means of a three fiber illumination assembly coupled with an in-plane object rotation. The high order diffracted spatial frequencies of the object are brought into the pass band of optical system by illuminating the object with tilted beams. The tilt produced at the fiber assembly plane is related to the dimension of the aperture, placed at the Fourier plane of the system. To span the 2D object spectrum at the Fourier plane, an in-plane object rotation procedure is applied at the object plane. The spectrum of the object is rotated as the object is rotated and illuminated with tilted beams. The corresponding object beam is interfered with a reference beam from the same source to record interferograms. All the recorded interferograms are stored in computer and de-convolution algorithm is applied to recover the synthesized spectrum. The image of the synthesized spectrum has three times improved resolution compared to the conventional image.

1. Introduction

Superresolution imaging techniques are used to resolve the objects beyond the classical limit without changing the parameters of the optical setup. Resolution of the optical system is limited either by diffraction phenomena or by CCD sampling [1]. The fact of overcoming the diffraction phenomena, occurred due to the wave nature of light, is called optical superresolution. The diffraction limit is related to the effective numerical aperture of the objective lens. Different techniques in the literature are reported to increase the numerical aperture using tilted beam illumination. Vertical-cavity surface emitting laser (VCSEL) arrays, lens arrays, or gratings [2–6] are used to increase the effective numerical aperture of the optical system. In these techniques the higher order spatial frequencies of the target object are recovered and they are used to enhance the object resolution. Fringes are also used as structured illumination to construct the synthetic aperture by heterodyning the higher spatial frequencies of the object into the pass band of the optical system used [7,8]. Digital holographic microscopy is also used to reconstruct the synthetic aperture by retrieving the phase features of the object [9–12]. The structured illumination produced by a fiber assembly or by a spatial light modulator (SLM) is used to recover the higher spatial frequencies of the object [13–15]. In our previous technique [13], a large number of fibers were used to illuminate the target object with different tilted beams. Each time, a different segment of the object spectrum is passed through the pass band of the system and the corresponding image is recorded. An adequate post processing of the recorded images can produce a final image with improved resolution.

In this paper, fibers at the assembly are reduced to three and this fiber reduction is compensated with the in-plane object rotation. The fiber assembly is followed by a 4f optical system, in which a square aperture is placed at the Fourier plane to quantitatively measure the resolution of the system. The position and orientation of the fibers at the fiber assembly are defined according to the aperture dimension. The central fiber of the fiber assembly, which is orientated along the optical axis of the system, illuminates the object so that the high frequencies of the spectrum formed at the Fourier plane are obstructed by the aperture. The object beam interferes with reference beam at the CCD plane in order to record an interferogram, called band limited image. A deconvolution algorithm is applied to the recorded interferogram, in which the reference beam phase effect is excluded from captured

* Corresponding author.
E-mail address: anwar_ktk@comsats.edu.pk (A. Hussain).

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images. This algorithm is a back propagation method in which the recorded interferogram is propagated back to the Fourier plane by taking the Fourier transform of the recorded interferogram. The spectrum of this interferogram revealed that only the central part of the object spectrum is retrieved. The target of this article is to retrieve missing higher spatial frequencies of the object by means of other two fibers and in-plane object rotation. During this operation of central fiber all other fibers are switched-off by using an optical switch. The fiber2 in the fiber array is a shifted fiber with respect to fiber1 by dimension of the aperture width which is used at the Fourier plane (the details of the system are given in Section 2). During the illumination with fiber2, the remaining two fibers are switched-off as explained before. The illumination produced by the shifted fiber2 also shifts the object spectrum at the Fourier plane so that another segment of the object spectrum is passed through the aperture. The image of this shifted segment of the object spectrum is interfered with the reference beam produced from the same source. The recorded interferogram is processed with the same algorithm applied to the first interferogram. During the post processing, the interferogram is propagated back to the Fourier plane where the segment is shifted back to the original position. In next step, all the other fibers are switched-off while fiber3 is switched-on to illuminate the object. Fiber3 is shifted $\sqrt{2}$ times dimension of the aperture with respect to the central fiber. During the illumination with fiber3, uppermost left corner of the object spectrum is brought into the pass band of the system. After capturing the image related to this fiber, the rest of the process is similar to the one applied to previous fibers. To reconstruct the full 2D object spectrum, in-plane object rotation with these fibers is used. The input object is rotated in plane by $\pi/2$, to bring the left portion of the object spectrum (left to the central part) into the pass band during fiber illumination. Now fiber2 is switched-on to illuminate the rotated object. This brings a new part of the object spectrum into the pass band/aperture lying left-perpendicular before rotation. Fiber3 illumination brings downward most left part of the spectrum into the pass band which is now the uppermost due to the rotation of the object. The interference patterns at the CCD plane occurred between each transmitted image and the reference beam are captured correspondingly. The computational process is the same as for the interferogram obtained before the object rotation. To retrieve the horizontal part of the object spectrum into the aperture, the object is rotated by $\pi/2$ step in the same direction. Fiber2 and fiber3 are operated sequentially in order to bring new segments of the object spectrum into the pass band and corresponding interferograms are recorded. In the last step, the object is again rotated by $\pi/2$ step in the same direction. This time fiber2 and fiber3 illuminations bring the right-perpendicular part of the object spectrum into the aperture and corresponding interferograms are recorded. All of the recorded interferograms are back shifted using de-convolution algorithm to the Fourier plane (explained above) where they are stitched together to obtain the overall synthesized spectrum. Finally, take the inverse Fourier transform of the synthesized spectrum results into the super-resolved image.

2. Mathematical model of object rotating

In this work the input object is illuminated by plane waves produced by the input fiber array followed by Lens2 placed adjacent to the input object as shown in Fig. 1. To recover the full spectrum of the input object, three fibers fixed at the fiber plane with different angles are used to illuminate the object. The input object is rotated to bring higher frequencies into the pass-band. The fiber plane and Lens2 coordinates are $(ma, na, 0)$ and $(0, 0, f)$, respectively, being f the focal length of Lens2 The input beam produced by the fiber and reached to the input plane is given by

$$A = \mathrm{Exp}(i\vec{k}\,\vec{r}). \quad (1)$$

In Eq. (1), vector k expresses the plane wave propagation vector, whose direction coincides with the one of the line joining each fiber in the assembly with the center of Lens2, and whose modulus is naturally given by the wave-number of vacuum, i.e. $2p/l$. Concretely, this vector is given by

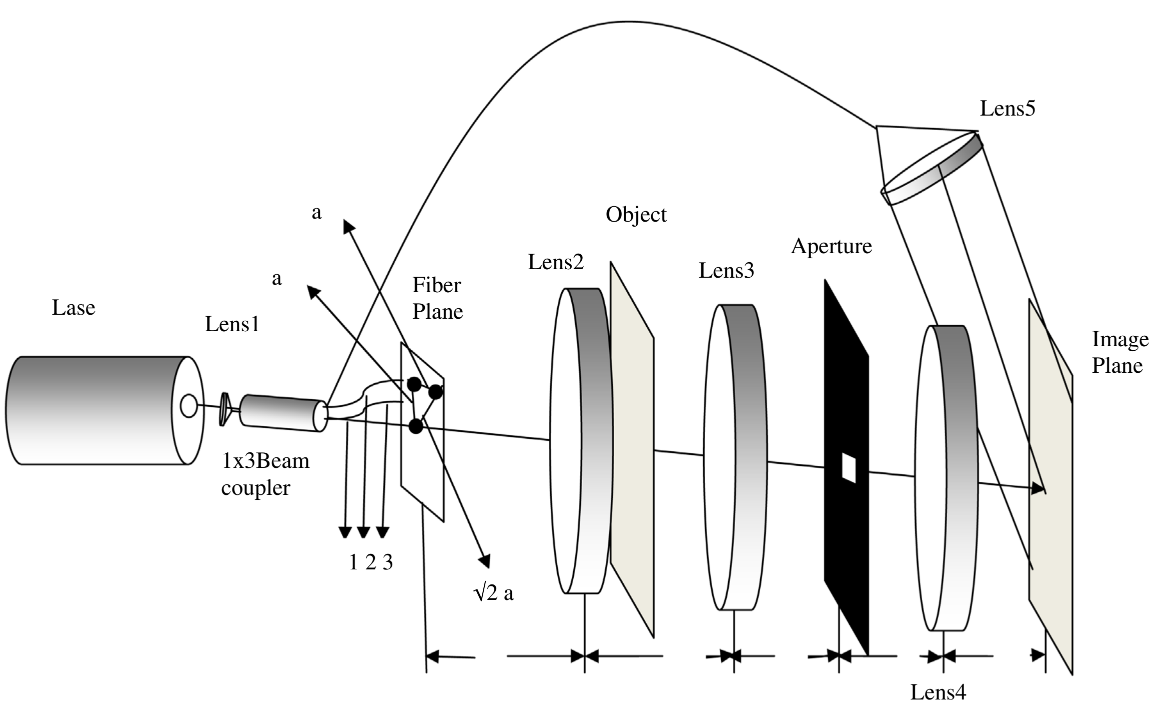

Fig. 1. Propose experimental setup for superresolution imaging using three fiber geometry coupled with in-plane object rotation.