Back focal plane confocal ptychography

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Abstract. This paper illustrates how the amplitude and phase of back focal plane distribution can be recovered in a confocal microscope system from several intensity images in the image plane. These will have a wide range of uses for imaging and sensing. We believe this method is complementary to the *V(z)* technique where the sample is defocused. The field generated in the back focal plane may be processed by virtual propagation which averages noise in a highly efficient manner. In this paper, we demonstrate that the phase information on the back focal plane can be recovered using ptychography with no need to modify the optical configuration and employ an interferometer. This phase information plays a crucial role in sensitivity of surface plasmons resonance biosensing systems.

Introduction

Wave fields are characterized by their amplitude and phase. Measurement of the intensity is relatively straightforward although in many cases phase measurement requires more involved instrumentation. Even in optics where coherent detection and interferometry allow one to reconstruct the phase it is often more convenient to reconstruct the phase from the intensity on account of the far simpler instrumentation involved with intensity only measurement and the greater flexibility conferred when the requirement for coherent detection is removed.

Phase reconstruction from intensity images has a long and venerable history starting from the famous Gerchberg and Saxton algorithm [1], through to transport of intensity [2] and ptychography [3,4]. A single intensity image does not allow one to reconstruct the phase as any arbitrary phase can be associated with the measured intensity or its square root the amplitude. The key is that when the field transforms to another plane the process of its transformation depends on the phase distribution, so that provided sufficient constraints can be applied the phase of the distribution can be recovered. For instance, consider the transport of intensity approach [2], the intensity at one plane does not give any phase information, but the evolution of the intensity as the field propagates is determined by the phase distribution. The information from the two planes thus fixes the phase as well as the amplitude.

In many imaging situations one has access to two planes which are related by a Fourier transformation. This occurs in optics where the image plane and the back focal plane are connected by a Fourier transformation [4]. In fact, the relation between the two detection planes does not need to be a Fourier transform, however, this relation is both efficient computationally and physically realizable.

In recent years reconstruction algorithms have become increasingly popular. Obviously, improvements in computational power have played a significant part, but also the available algorithms are much more resistant to stagnation, which is a problem that beset some early algorithms [5].

The ptychography approach has been successfully used by many authors, is highly robust and provides a powerful means of phase reconstruction. The method has been described more fully elsewhere but for completeness we review the crucial stages in the process.

1. Record intensity only by illuminating overlapping regions of the desired 'image' (plane I) and record at a transform plane (plane T).
2. Make an initial guess of the distribution at the image plane by transforming the distribution at plane T, retain the phase of this distribution but correct with the known amplitude. Transform back to the image plane and apply the correction. The strength of this correction can be controlled within the algorithm. The correction will be applied to the whole of the sub region in the image plane. Since regions overlap this will apply the correction to other recordings from different sub-images. This ensures that the different images are connected
3. Repeat the procedure for different subregions.
4. Return to stage 2 (initial subregion) and continue until the stopping criterion is reached (normally that the residual errors between the transformed image and the measured intensities are below a preset threshold.

Back focal plane reconstruction

The most usual application of ptychography is to reconstruct images from their diffraction patterns. The sample is illuminated with several overlapping areas and the diffraction patterns are recorded which are used to reconstruct the amplitude and phase of the object. In our case it is the back focal (Fourier) plane we which aim to construct from a series of images in the detection plane. In other words in our work planes I and T are inverted compared to the usual case.

Figure 1 shows the schematic of our system. This shows a confocal type microscope (with the illumination path omitted for clarity), the pinhole is replaced by an array detector such as a CCD or CMOS detector. The light illuminating the microscope objective in the back focal plane is linearly polarized, this is important since the use of other polarization states will greatly complicate the reconstruction.

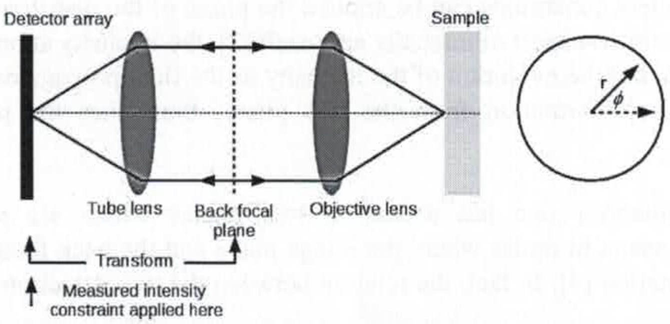

Fig. 1 Schematic of confocal microscope system, showing back focal plane. Circle on the right shows the back focal plane.

The linearly polarized light is incident on the sample with the radial position r in figure 1 being proportional to the sine of the incident angle. The angle ϕ determines the polarization state. Assuming the polarization is horizontal, the light at ϕ=0 degrees will be TM polarized and the light incident at 90 and 270 degrees is pure TE polarized and, of course, for light incident at intermediate angles the polarization state is mixed. The returning field can be determined by resolving the components. Even though the light is linearly polarized the different reflection coefficients for TM and TE polarization states will not return linearly polarized light to the back focal plane and there will be components of field orthogonal to the original direction. The light used for the measurement is detected on the detector array and the Fourier transform relation between the two planes is valid for single polarization state, for this reason a polarizer should be inserted into the path between the back focal plane and the detector array. Although the system generally has a very high numerical aperture between the back focal plane and the image plane so that there are substantial field components in the axial direction, the path to the image detector has low NA so the detected field lies in plane with the detection plane array for both TE and TM polarizations. In the schematic the NA of the objective and tube lens are shown of similar magnitude but in practice the detection NA is smaller by a factor of the magnification (at least 100 and often >1000 in our experiments).

Simulation results

The ptychography algorithm has been implemented as described in the introduction. The sample modelled was gold (47nm) in an aqueous environment to support surface plasmons excited from index 1.52. Surface plasmons are excited albeit at the extreme angles of the microscope objective.

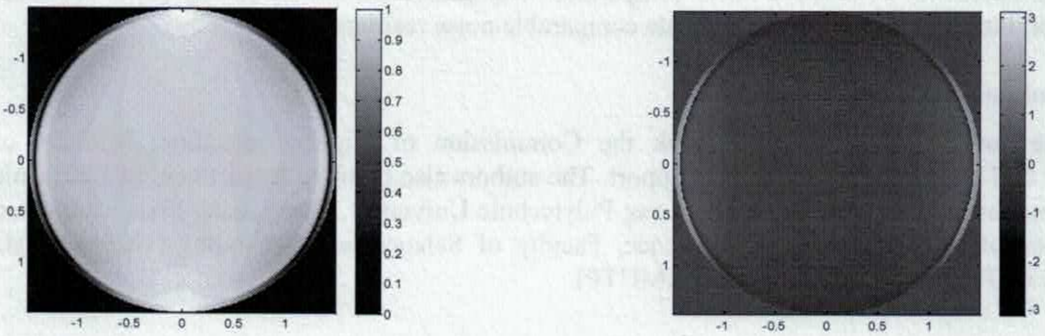

Fig. 2 Reconstructed amplitude and phase of back focal plane distribution from intensity only images in the image plane. The axes represents units of NA (microscope objective is 1.49). The left image in amplitude and the right one is phase.

The reconstruction used 20 circles in the back focal plane touching the outer aperture of the lens and the radius of each region was 90% the radius of the whole aperture. The convergence was reached rapidly in only 16 iterations. Since we now have the amplitude and phase of the field this may be propagated computationally to mimic the exact response of the embedded interferometer presented earlier by the authors [6], the advantage here being apart, of course, from the simple instrumentation, is that there is no need to impose a pupil function on the system during the measurement since it can be done computationally. This has a great advantages as it allows one to make the effective aperture even wider than the physical aperture. This greatly reduces artefacts making it more feasible to carry out a biological sensing experiment under a microscope objective as will be discussed in a later publication. Figure 3 shows a similar image to figure 2 except an additional 10nm layer of refractive index 1.33 is inserted which increases the surface plasmon k-vector even more. The reconstruction allows us to measure the phase information on the back focal plane. In this paper, we have demonstrated one of the applications of ptychography by recovering the amplitude and phase of back focal plane distribution in a confocal microscope system.

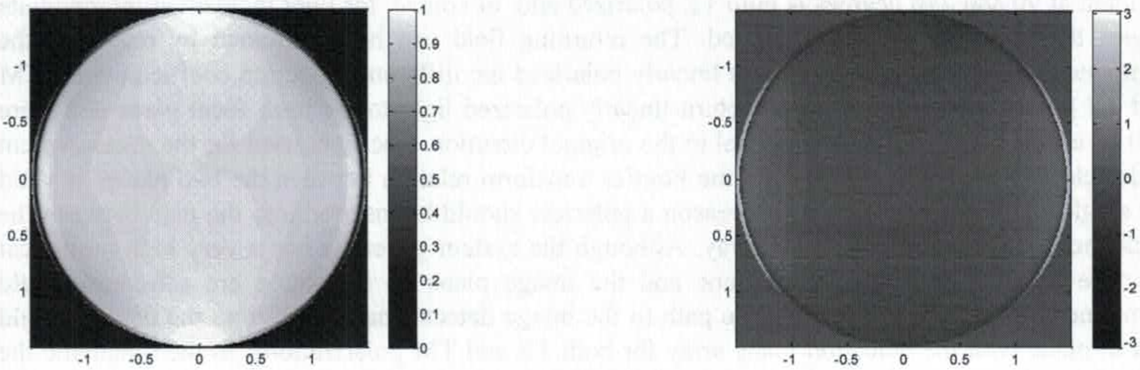

Fig. 3 Reconstructed back focal plane distribution for the same case as figure 2 except an additional 10nm layer of dielectric (index 1.5) is placed one the gold.

Conclusion and further work

Ptychography appears to have great potential for back focal plane reconstruction. We are currently implementing the system on our experimental system and evaluating the effect of noise and different surface wave distributions including those with little amplitude variation that is essentially phase only variations. A detailed noise comparison with embedded interferometry [6] is required, although preliminary measurements indicate comparable noise resilience.

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References

[1] R. W. Gerchberg and W. O. Saxton, A practical algorithm for the determination of the phase from image and diffraction plane pictures, *Optik* **35**, 237 (1972).

[2] C. Zuo, Q. Chen, and A. Asundi, Boundary-artifact-free phase retrieval with entres the transport of intensity equation: fast solution with use of discrete cosine transform, *Opt. Exp.* **22**, 9220-9244 (2014).

[3] W. Hoppe, Beugung im inhomogenen Primärstrahlwellenfeld. I. Prinzip einer Phasenmessung von Elektronenbeungungsinterferenzen.*Acta Crystallographica A* **25**(4): 495 (1969)

[4] J M Rodenburg and H M L Faulkner, A phase retrieval algorithm for shifting illumination *Appl. Phys. Lett.***85**(20) 4795 (2004).

[5] J. R. Fienup, Phase retrieval algorithms: a comparison, *Appl. Opt.* **21**(15), 2758-2769 (1982).

[6] B. Zhang, S. Pechprasarn, M.G. Somekh: Quantitative plasmonic measurements using embedded phase stepping confocal interferometry, *Opt Exp.* (2013).