Phase front reconstruction by optical phase conjugation

D. Radnatarov*, S. Kobtsev
Novosibirsk State University, Pirogova str., 2, Novosibirsk, Russia 630090

ABSTRACT

This study proposes a method for reconstructing the wavefront phase of coherent radiation using a physical model of light propagation, instead of Fourier transforms. The method uses a back-propagating beam with a conjugated optical phase to efficiently account for real properties of optical elements. Experimental demonstration is provided of beam formation in a real optical system with a pre-defined transverse intensity distribution with the help of a phase spatial light modulator (SLM), whose state is calculated by using the proposed method on Zemax software for light propagation modelling.

Keywords: Phase retrieval, wavefront reconstruction, SLM

1. INTRODUCTION

A method of optical wavefront phase reconstruction is proposed consisting in extraction of the complex amplitude phase of electric field from two known distributions of the radiation beam intensity at two reference surfaces. This method is fairly universal and allows characterisation of the radiation wave front emitted by various laser sources, including semiconductor lasers. The problem of finding the radiation wave front emerges in many applications where it is required to create laser beams with a specific profile, for example, in active media pumping, and so forth.

Similar existing iterative methods of phase reconstruction rely on a process that minimizes the difference between the observed intensities and those obtained by multiple simulation of forward and backward propagation of light between the reference planes. If a reference plane is located at the focal plane of a lens or in far field, then the mathematical apparatus of Fourier optics is used and light propagation in both directions may be calculated by forward and inverse Fourier transforms. This principle powers the most popular methods, such as Gerchberg-Saxton (GS)[1,2] and Fienup[3,4]. One of the drawbacks of these algorithms is their use of the thin lens approximation, which does not allow factoring in of all the properties of real optical elements (in particular, the introduced aberrations of the wave front), thus significantly limiting applicability of these methods and the design of devices where they are used. The present work proposes an iterative algorithm of phase reconstruction where forward and inverse Fourier transforms are replaced by a model of physical light propagation and simulation of back-propagation is carried out through wave front phase conjugation. The proposed method may be used with various mathematical models of light propagation including calculation of the Rayleigh-Sommerfeld integral and the angular spectrum approach, which take into account the real properties of optical elements.

*d.radnatarov@nsu.ru

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2. PHASE FRONT RECONSTRUCTION ALGORITHM

The diagram of our implementation of the proposed algorithm is shown in Fig. 1. Similar to the original GS algorithm, this method of phase reconstruction from measured beam intensity profiles includes four stages. In the first stage, propagation of the wave front is simulated from the first reference plane to the second through an arbitrary optical system. In the second stage, the wave front at the second reference plane is conjugated and the measured (or desired) intensity profile is substituted. In the third stage, propagation of the conjugated phase front is modelled from the second plane back to the first through an inverted optical system. In the fourth stage, the wave front at the first plane is conjugated and the measured intensity profile is substituted once more. This closes the cycle and the next iteration begins. Initially, the phase in the first plane is either set randomly, or according to some known approximation (flat, spherical with a known curvature, &c).

Because the algorithm relies on a physical model of light propagation, it is possible to place an arbitrary optical system between the two reference planes (in which the intensity profile is measured), and the properties of this system will be taken into account to the extent that the chosen propagation model is able to do it. It is the selected method of light propagation modelling that governs the minimal resolution to which the beam intensity profiles need to be measured as well as how complicated and fine-grained the optical system may be.

One of the features of the proposed method is that it only uses a model of forward light propagation. This may be quite convenient because existing mathematical packages, libraries written in different programming languages, and even specialised software may be used that were designed and optimised for the problem of light propagation.

In our case, modelling of the optical system was performed with OpticStudio (Zemax) and its built-in instrument Physical Optical Propagation (POP) for light propagation modelling. The optical system is also schematically shown in Fig. 1. The distance from the 1st plane to the source plane and the lens was equal to 5 mm, whereas the distance from the lens to the 2nd plane was 20 mm, the lens focal length being 10 mm. Radiation with a specified initial phase and intensity distributions in the source plane passed the first plane, plane-concave lens, and reached the second plane, after which it propagated through the inverted optical system and reached the following plane that played the role of the conjugated first.

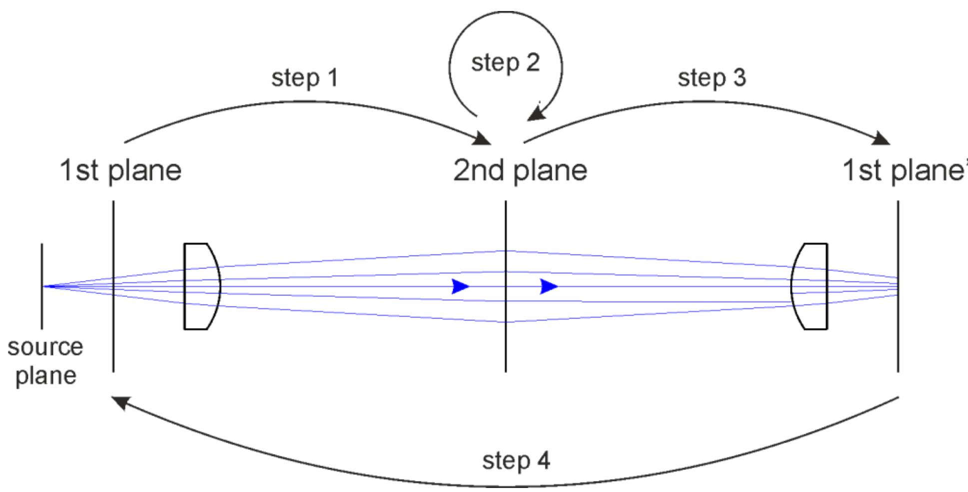


Figure 1. Implementation of the proposed algorithm: step 1 – forward propagation of light from the first plane to the second through the optical system; step 2 – complex conjugation of the wave front, substitution of the distribution measured at the second plane for the real part of the profile; step 3 – forward propagation of light from the 2nd to the 1st plane through the conjugated (inverted) optical system; step 4 – complex conjugation of the wave front, substitution of the distribution measured at the first plane for the real part of the profile.

For demonstration of the method's possibilities, the following numerical experiment was carried out. Initially, beam propagation was simulated from the source plane through the first plane and optical system up to the second plane. Information about the intensity profile was used for implementation of the algorithm that restored the phase in both planes. The phase extracted by the algorithm was then compared to that calculated initially.

3. RESULTS

Three initial beams were simulated: a Gaussian beam with a flat wave front, Bessel beam of the 1st order, and a Bessel beam of the 2nd order. The Bessel beams were specified in the source plane as Gaussian beams with a curled wave front. Fig. 2 presents the results of modelling the intensity and phase profiles of the respective beams in the second plane. It should be noted that the phase of the Gaussian beam in this case, instead of a plane, is relative to a sphere whose radius is determined by the pilot beam. For a Gaussian beam, the sphere radius is equal to the distance from the beam waist equal in our configuration to 5 mm. It should be further pointed out that the artefacts present at the edges of the phase profile are not important because the radiation intensity in these areas is close to zero. Actually, it is the very absence of radiation in these areas that gives rise to incorrect phase values.

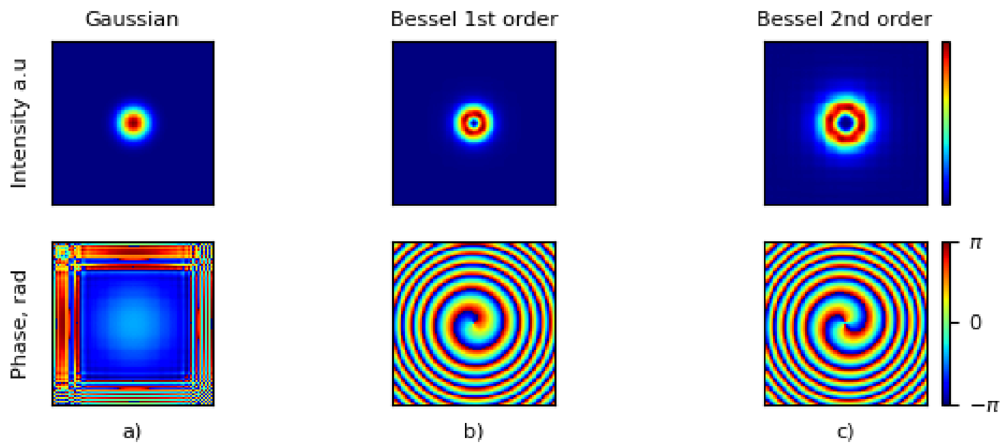


Figure 2. Intensity and phase profiles in the second plane calculated for a) Gaussian beam, b) Bessel beam of the 1^{st} order, c) Bessel beam of the 2^{nd} order.

Given in Fig. 3 are the results of the algorithm for reconstruction of the wave front phase for a Gaussian beam after the first step, viz. the intensity profile is the calculation result before the substitution of the measured one. As one can see from the figure, this algorithm allows correct reconstruction of the beam wave front from two measurements of the Gaussian beam intensity profile. The results are similar for the Bessel beams of different orders (see Fig. 4 and 5). It may be also mentioned that convergence of the iterative process in the case of the 1st-order Bessel beams depended on the initial phase distribution. For instance, when the initial wave front was flat, the process did not converge. For the 2^{nd}-order Bessel beam, in some instances of random initial phase distribution, the solution approached toward a 1^{st}-order beam with a curved phase profile. In the majority of attempts, however, this iterative process led to an accurate identification of the Bessel beam order.

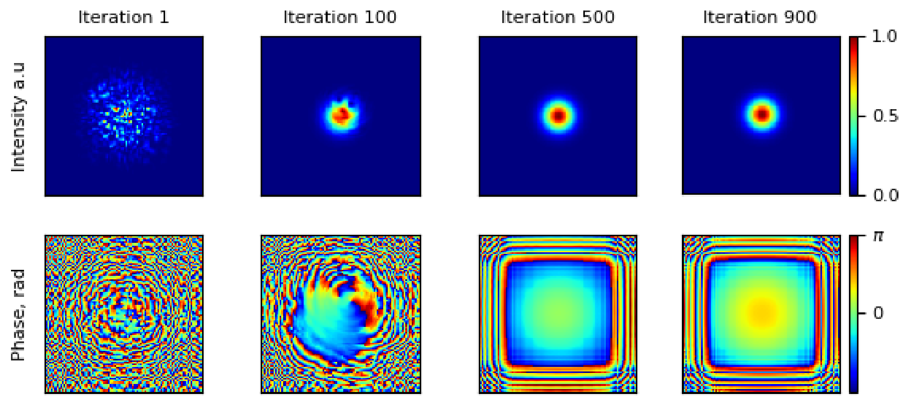


Figure 3. Intensity and phase profiles in the second plane during reconstruction of the Gaussian beam phase.

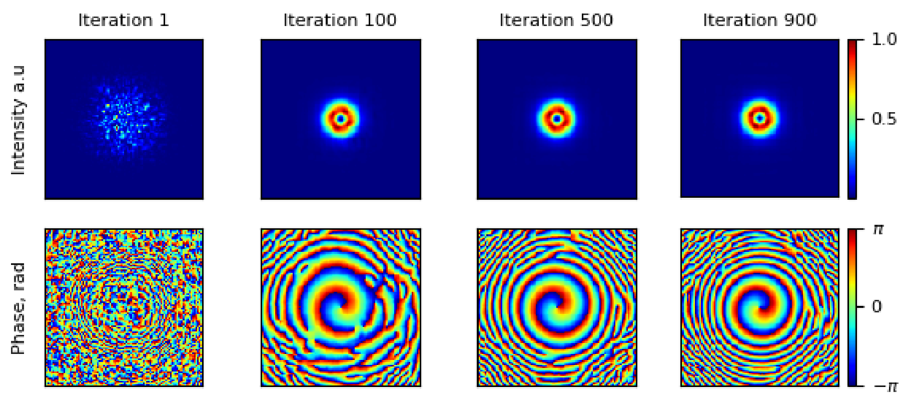


Figure 4. Intensity and phase profile in the second plane during phase reconstruction of the 1st-order Bessel beam.

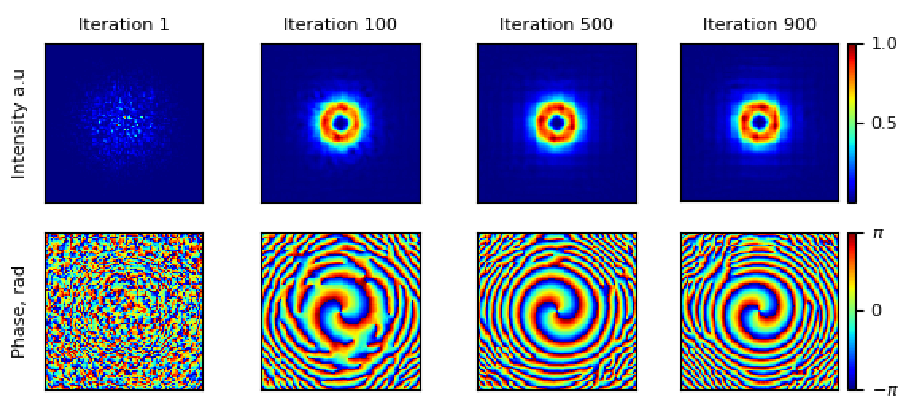


Figure 5. Intensity and phase profile in the second plane during phase reconstruction of the 2nd-order Bessel beam.

The presented reconstruction algorithm may be applied not only for restoration of the wave front of light beams, but also for calculation of the states of adaptive mirrors or spatial light modulators (SLM) used to create beams with desired intensity distributions. We chose an implementation of the latter function for demonstration of the method's abilities. The problem of image formation with a phase SLM is usually solved by the Gerchberg-Saxton algorithm, which allows computation of a diffraction mask for creation of an image in the far field or in the focal plane of a thin lens. But computation of a phase mask that would form an image in the near field is a more complicated problem, which we solved by application of our algorithm.

The layout of the experimental set-up for generation of images with a phase SLM is shown in Fig. 6. The output of a fibre laser emitting at 1,560 nm was delivered through a single-mode fibre to collimator FC. A phase SLM (Pluto 2.1 Holoeye Photonocs AG) with resolution of 1920x1080 pixel and pixel size of 8 μm was illuminated by a 2-mm Gaussian beam with vertical polarisation necessary for correct operation of the SLM. The reflected beam was registered with a CCD camera (Point Grey CMLN-13S2M). The distance between the SLM and camera was L = 120 mm, the effective Fresnel number $N_F = \omega/2^2/L\lambda$ for the sensor plane being equal to 5.3, thus satisfying the condition of near field (N_F>1).

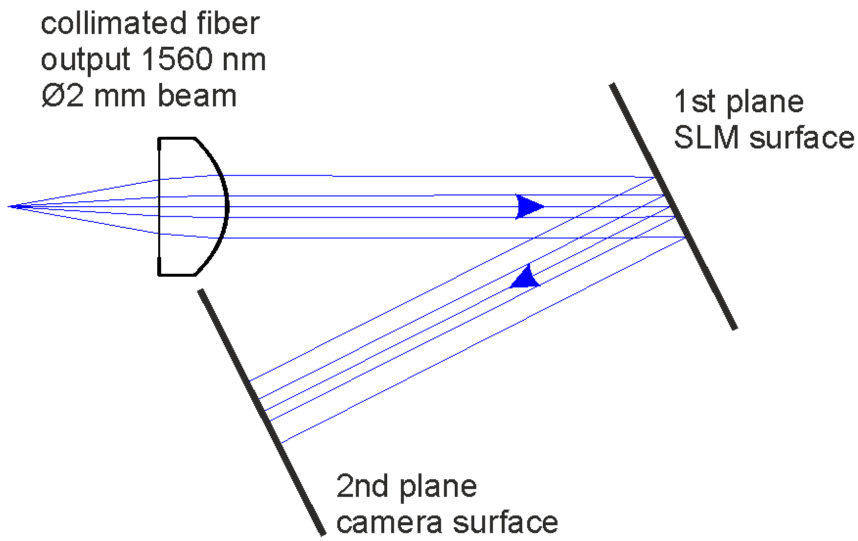


Figure 6. Diagram of the experiment on creation of a desired beam profile with a phase spatial light modulator (SLM).

The experimental results of image formation with a phase SLM are presented in Fig. 7. In calculations, the SLM plane corresponded to the first plane and the beam intensity in it was that of a Gaussian beam with a 2-mm diameter. The camera sensor plane corresponded to the second plane of the algorithm.

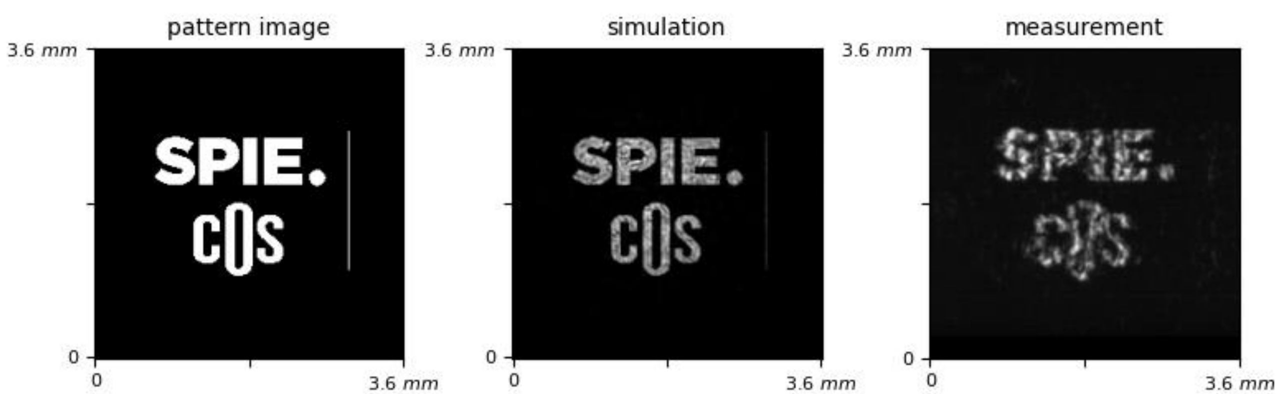
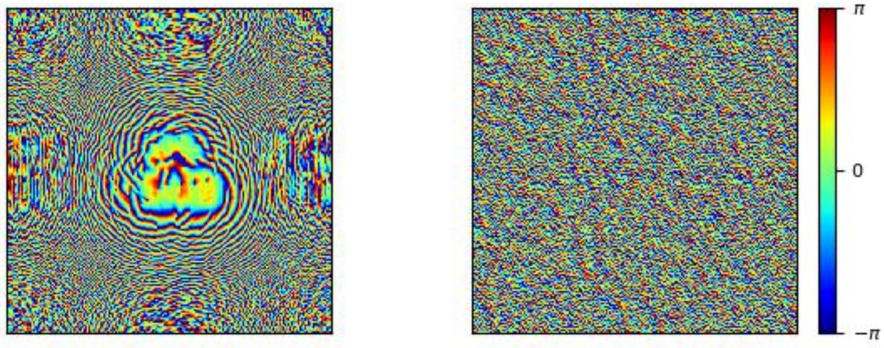


Figure 7. Results of the experiment on formation of a desired beam profile with a phase SLM.

It can be seen from the Figure that the proposed algorithm does allow computation of the phase mask that forms the desired image in the selected plane. It should be pointed out that in this case, the SLM functions as an adaptive mirror and modifies the phase relatively weakly (see Fig. 8a), redistributing the intensity for composition of the desired beam profile, as opposed to a diffraction element that leads to every part of the beam participating in formation of the entire image.



a) b)

Figure 8. Phase masks for generation of the image shown in Fig. 7: a) the mask for this image in the near field produced by the proposed method and b) the mask for generation of this image in far field or focal plane of a thin lens calculated with the GS algorithm.

4. CONCLUSION

This work presents a new iterative algorithm for reconstruction of laser radiation phase, in which forward and inverse Fourier transforms of the wave front were replaced by a physical model of light propagation, and a wave front with conjugated optical phase is used for modelling of back-propagation. Also demonstrated is the possibility of phase reconstruction for Gaussian and Bessel beams of different orders. This work also shows experimentally the possibility of generation of beams with desired intensity distribution in the near field with the aid of a phase spatial light modulator (SLM) whose state is calculated by the proposed method using the commercial software suite Zemax for modelling of light propagation.

5. ACKNOWLEDGEMENTS

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