Designing free-form optics for high-quality Gaussian beam tailoring from diode lasers for Ti:Sa laser pumping

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ABSTRACT

This paper discusses adapting the Gerchberg-Saxton algorithm to design refractive free-form optical elements for custom beam tailoring, particularly to convert powerful diode laser outputs into high-quality Gaussian beams. A distinctive feature of the algorithm is its ability to design thin-profile optical elements (less than 5 wavelengths), manufacturable with high precision using industrial grayscale lithography. Experimental results are presented for transforming a 455 nm, 6 W diode laser beam into an efficient pump source for Ti:Sa lasers, demonstrating the algorithm's potential to enhance diode laser applications in scientific and industrial settings.

Keywords: Beam shaping, beam tailoring, free-form optics, GS algorithm, diode laser

1. INTRODUCTION

Recent progress in semiconductor lasers led to development of powerful and comparatively affordable diode lasers in the visible spectral range. One of their promising applications is pumping of broadly tuneable titanium-sapphire lasers and dye-jet lasers[1,2] using powerful blue or green lasers. At this point, this is predominantly achieved by complicated and expensive green DPSS lasers. Attempts were made to pump Ti:Sa lasers directly with powerful diode lasers, but one of the primary issues here remains low beam quality of diode lasers, which complicates efficient focusing inside an optically active medium[3–5]. Even though the output power of modern diode lasers became comparable with that of DPSS lasers, the problems lies in the complex transverse intensity distribution in the diode laser beams that does not allow pumping Ti:Sa/Dye-jet lasers as efficiently as with DPSS lasers.

One of the potential solutions to this problem is application of free-form optics—optical elements with specially calculated working surfaces[6,7] — that transform the output beam of a diode laser into a form better suited for efficient pumping. It is important to bear in mind that such optical elements are linear and cannot, in general, modify the geometrical factor of the beam. This poses a limit on the possibility of transformation into Gaussian beams of the powerful diode laser output. Nonetheless, a number of applications allow such transformation of the pumping beam as to improve efficiency. For instance, it was earlier demonstrated that it is possible to so transform the beam of a diode laser[8], as well as that of an LED source[9–11] with free-form optics. Besides, it has also been shown that the beam quality of classical laser radiation may be improved with such optical elements[12]. Thus, free-form optics opens up the possibility of transforming light beams produced by different sources.

This work presents the first results of development of an optical system relying on free-form elements for pumping Ti:Sa laser with a commercially available powerful blue diode laser.

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2. GS ADAPTATION

Powerful diode lasers produce typically complex structure of the output radiation beam, which makes it difficult to apply standard methods, such as that of stationary phase[13] or solving the equation of Monge–Ampere[14–16], for achievement of satisfactory results in beam quality improvement. Therefore, we developed a special algorithm on the basis of the well-known Gerchberg–Saxton (GS) algorithm[17,18] for design of refraction phase masks that can efficiently transform a beam.

Shown in Fig. 1, is a diagram of the modified GS algorithm that produces a solution for smooth wave front transforming the input beam in the desired way. The primary idea of this method consists in sequential finding of a set of phase profiles in the source plane. Each of these profiles results in gradual transformation of the beam in the target plane, successively approximating the desired intensity distribution. The graphic plot shows an example of converting a Gaussian beam into a rectangular one. As the initial approximation in the source plane, we chose a flat wave front corresponding to a Gaussian beam with a certain characteristic size in the target plane. After than, beam morphing is performed, or sequential calculation of profiles from the initial (Gaussian) one to the desired one (in this case, rectangular). For each intermediate profile, the phase profile is calculated by the classical GS method where the solution for each profile is taken as the initial approximation for the next one. On condition that successive intensity profiles evolve gradually, the GS algorithm preserves refractive character of the wave front, which eventually results in generation of the desired phase profile for transformation of the initial beam.

One of the goals of the proposed approach is selection of the algorithm, which will convert the initial beam into the target one. Among the possible methods we see using a sequence of images generated after application of a Gaussian filter with a shrinking kernel size [13]. However, this method runs into the problem of selection of the initial approximation because it is not always possible to correctly shape the beam profile into the desired condition only by filtering. The present work proposes an alternative approach based on solving the thermal conductivity equation. The idea consists in application of this equation to the initial intensity profile, thus leading to its gradual "blurring". Adding into the equation an extra term corresponding to the target profile with the opposite sign, it is possible to ensure that this target profile becomes a stationary solution of the equation. This allows obtention of a succession of profiles evolving from the initial one towards the target.

It should be noted that conversion of laser beams often involves an initial Gaussian beam that has to be reshaped because Gaussian beams produced at the output of a single-mode optical fibre is the most convenient when a beam with a predictable intensity distribution and wave front is necessary. In our case, however, transformation has to proceed from a target profile towards a Gaussian one, thus avoiding the requirement of storing the entire sequence of solutions to the thermal conductivity equation. This is done to simplify calculations because the Gaussian function is well defined and differentiable over its entire plane, and this removes complications arising when solving the equation with additional terms.

For implementation of the GS algorithm, it is possible to use both a standard optical system with a lens and more complex optical layouts by application of physical models of radiation propagation[19].

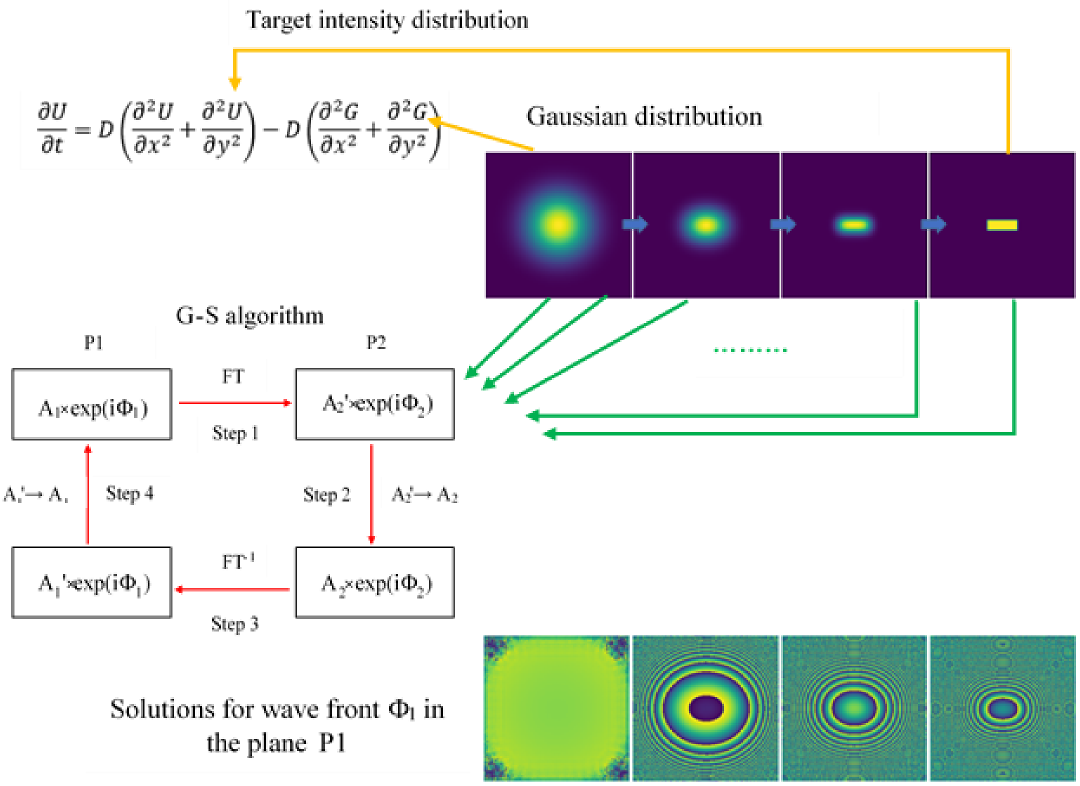

Figure 1. Modified GS algorithm.

3. DIODE LASER WAVEFRONT RESTORATION AND TAILORING

A diode laser beam was characterized using the coherent wavefront approximation using the method described earlier in papers[20,21]. This method includes the measurement of beam intensity profiles in several planes, on the basis of which the absolute values of the complex amplitudes of the fields are extracted. Next, the direct propagation of radiation between the planes is modeled, where the calculated amplitudes are replaced by the measured ones. The scheme of the algorithm is shown in Fig. 2.

The radiation of a blue diode laser with a wavelength of 455 nm was collimated by a lens with a focal length of 20 mm. The accuracy of the final solution for the phase distribution in the last plane (110 mm) depended on the accuracy of the initial approximation for the wavefront in the first plane (0 mm). It should be noted that the beam diverged significantly mainly along the vertical axis, so the radius of curvature of the wavefront for it was assumed to be equal to R = 150 mm. At the same time, along the horizontal axis, the wave front was considered almost flat.

After finding a solution for the last plane, the beam was propagated back using a similar technique to determine the wavefront parameters in the first plane. This solution was then used to model phase distributions in intermediate planes. Thus, fairly accurate solutions were found for planes at distances from 0 to 50 mm, since the method well restores the main characteristics of the radiation intensity distributions in these planes.

Fig. 3 shows the calculated and measured beam profiles for the plane at a distance of 10 mm from the initial one, as well as their sections along the x axis. As can be seen from the graphs, the solution found describes the propagation of radiation quite accurately.

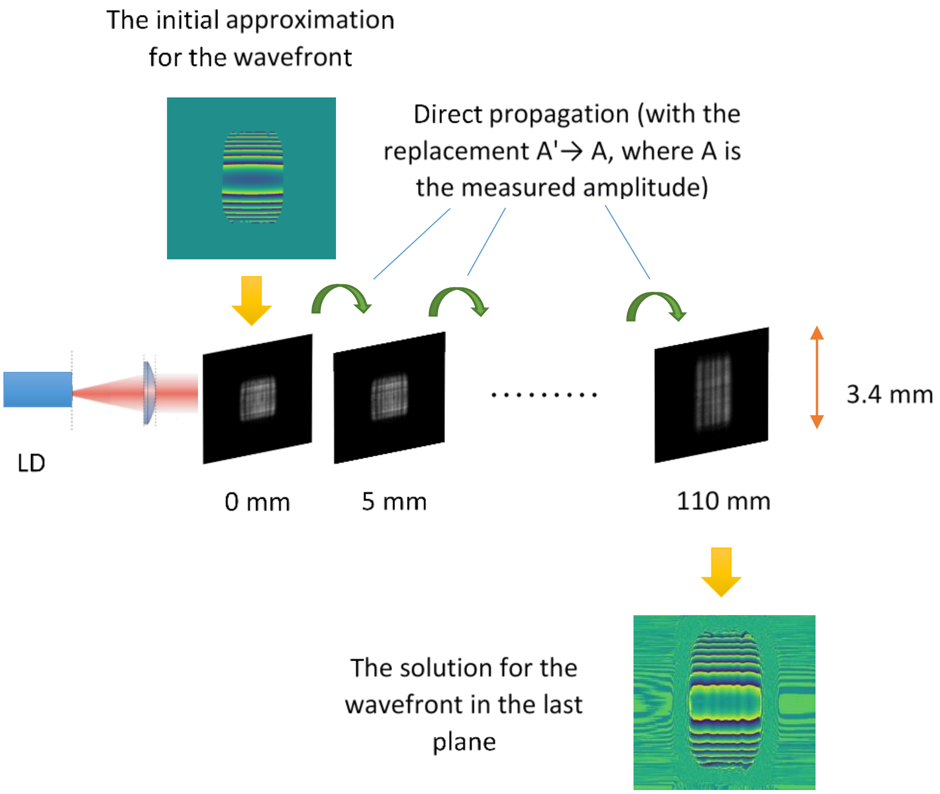

Figure 2. Algorithm of wave front reconstruction for a diode laser.

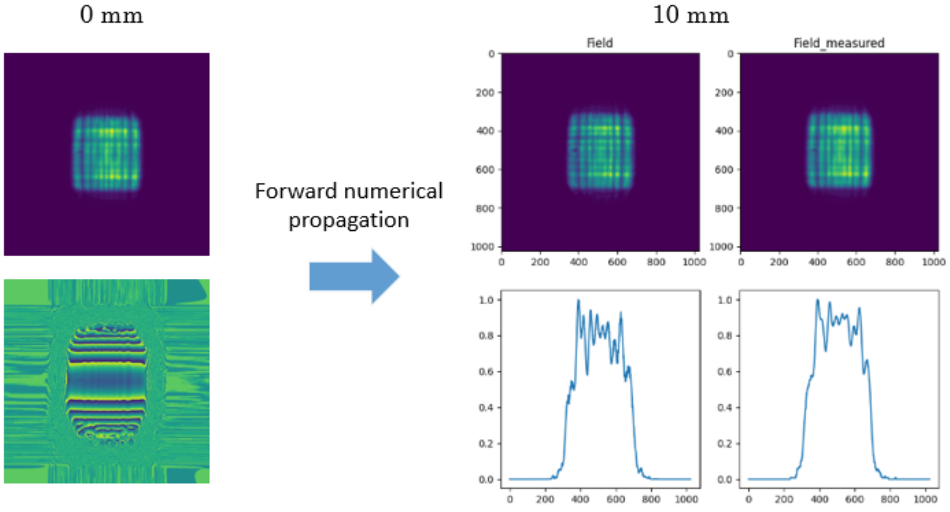

Figure 3. Comparison of the measured profile with the beam intensity profile from simulation of propagation of the calculated wave front.

During the following stage, a solution for the phase mask in plane P1 (Fig. 4) was found using the modified GS algorithm that transforms the intensity profile of the diode laser's output beam into a beam with a Gaussian intensity distribution in plane P2. In the process of calculation, also the phase mask for plane P2 was found that flattens the wave front. At the output of the optical system, the beam has a flat wave front and intensity distribution approaching Gaussian

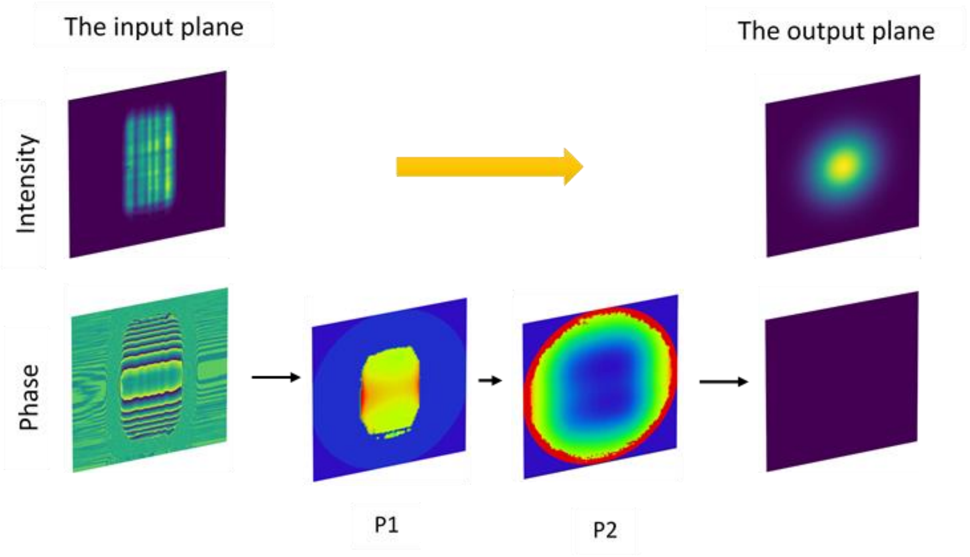

Figure 4. Scheme of beam transformation using two free-form surfaces.

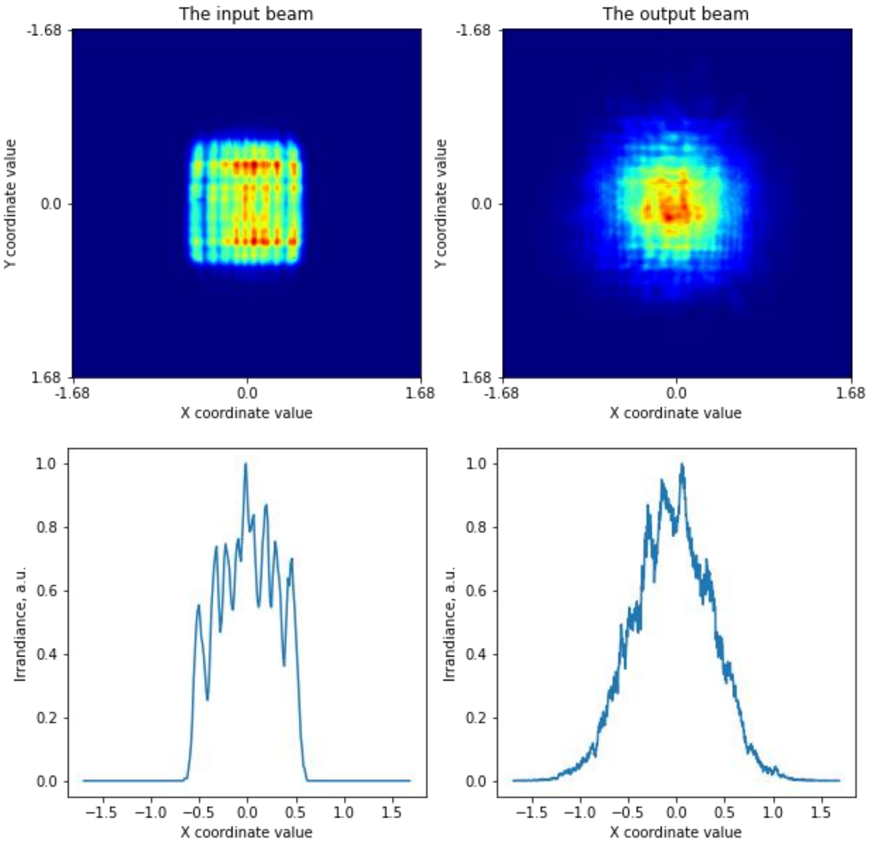

Figure 5. Modelling of beam conversion in Zemax. Horizontal intensity profiles are given at the bottom.

The diameter of the Gaussian beam in plane P2 was chosen so as to minimise the depth of the phase mask in plane P1. This allowed to obtain a solution for optical surface P1 with the depth not exceeding 10 wavelengths, which is equivalent to approximately 5 µm. The mask depth for plane P2 did not exceed 8 wavelengths, thus meeting the technical requirements of the grey-scale lithography [22–24] that allows fabrication of elements with the surface depth of up to 10 µm.

For verification of the produced results, the entire process of beam transformation was modelled in Ansys Zemax OpticStudio with the Physical Optics Propagation tool. Fig. 5 presents the modelling results that demonstrate that the designed optical system efficiently transforms the input beam according to the design parameters

4. CONCLUSION

This work presents the first steps in development of an optical system for transformation of the output beam from a powerful blue laser diode using free-form optical elements for pumping a Ti:Sa laser. Experimental measurement of the output beam of the diode laser was performed, including approximated calculation of the beam wave front. A modified Gerchberg–Saxton (GS) algorithm is proposed and implemented on the basis of directional morphing of the intensity profile, thus allowing calculation of the surface shape of free-form optical elements. Solutions have been obtained for the optical reflective elements that ensure transformation of the diode laser beam according to the design requirements.

As the next step, the Authors are planning to fabricate the designed optical elements by grey-scale lithography and to conduct experimental test of the possibility of transformation of a diode laser output beam.

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