Applying Refractive Beam Shapers for Spectral Beam Combining with Volume Bragg Gratings

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ABSTRACT

The technique of combining the laser beams with proximate wavelengths by a train of volume Bragg gratings operating as narrow band spectral mirrors allows reaching extremely high resulting power. Performance of these volume Bragg gratings in terms of reflectivity, stability of spectral characteristics depends on their temperature, especially on the temperature profile being a result of interaction of the incident or passing through radiation of powerful laser with material of the grating. The most dangerous effect of thermal lensing appears as a result of heating by laser radiation. The temperature profile in a grating is determined by the intensity profile of a laser beam applied, conditions of thermal conductivity, and energy exchange with environment. The Gaussian intensity distribution in typical laser beams leads to higher temperature in the central part of a grating and, hence, causes nonuniform shift of Bragg wavelength across the aperture and thermal lensing. Homogenizing of the temperature profile over the working field of a volume Bragg grating would mitigate radial gradient of temperature and increase brightness of a combined beam. This can be realized through applying the beam shaping optics, for example refractive field mapping beam shapers. They provide high flexibility in building various optical setups due to their unique features: almost lossless intensity profile transformation, providing flattop, super-Gauss or inverse Gauss profiles. Different profile shapes can be achieved with the same beam shaper, saving of the beam consistency, high transmittance and flatness of intensity profile, extended depth of field, capability to adapt to real intensity profiles of TEM_{00} and multimode laser sources. Combining of the refractive field mapping beam shapers with other optical components, like beam-expanders, relay imaging lenses, anamorphic optics makes it possible to generate the laser spots of necessary shape, size and intensity distribution.

This paper describes a comparison of quality (M^2) of Gaussian and super-Gaussian beams diffracted and transmitted by reflecting volume Bragg gratings used for spectral beam combining. Both, mathematical modelling of thermal lensing and experimental results with high density spectral beam combining of 150 W laser beams are described. It was found that the use of super-Gaussian beams results in smaller gradient of temperature across the aperture and, therefore, smaller thermal lensing.

Keywords: beam shaping, beam combining, volume Bragg grating, flattop, supergauss, inverse Gauss, high power laser, homogenizing.

1. INTRODUCTION

High aperture volume Bragg gratings (VBG) recorded in photo-thermo-refractive (PTR) glass have been successfully implemented for spectral beam combining (SBC) of fiber lasers up to kilowatt power level recently[1,2] and they are promising candidates for future SBC systems up to hundreds of kilowatts. In the realized combining scheme each narrow-band VBG reflects particular laser beam in the same angular direction with other beams of slightly different wavelengths for which this grating is almost transparent. Due to the complex chemical composition of the PTR glass each VBG demonstrates residual material absorption which becomes a source of its own heating. At 100kW laser power operation each grating is supposed to be actively cooled by gas flow in order to manage the heat load. As a result, the radial profile of the heating follows the profile of the beam intensity which is usually Gaussian. The thermal thickness

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expansion of the grating plate leads to corresponding Gaussian phase distortion that affects the beam quality. This parasitic phase distortions from multiple transmitted beams are the main limitation of the SBC system performance. One promising approach to overcome this problem is the use of super-Gaussian beams for SBC. Such beams have more uniform intensity profiles then ordinary Gaussian ones and though they are characterized by initial beam quality factor slightly higher than unity they have demonstrated much more stable behaviour when propagating through heated gratings. To convert the Gaussian intensity profile of initial laser beams to super-Gaussian one it is suggested to apply refractive field mapping beam shapers[3,4,5], like *πShaper*, demonstrating high level of flexibility in realization of different intensity profiles with using the same beam shaper. These beam shapers transform the laser beam profile in a control manner and have some interesting features that will be discussed and presented in the paper. There will be considered optical layouts with using volume Bragg gratings as well as *πShaper*, their behaviour depending on conditions of a particular beam combining system as well as experimental results.

2. THEORETICAL CONSIDERATIONS

The basic principles of spectral beam combining with using VBG were considered in the paper[2]. One of possible optical layouts is presented in Fig. 1.

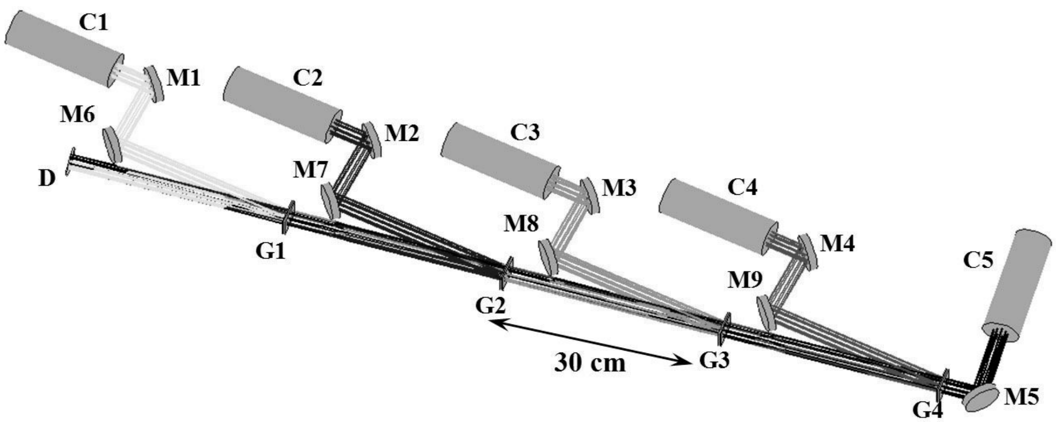

Figure 1 Optical layout of spectral combining of several fiber lasers:
C1-C5: Fiber laser with collimators, M1-M9: Steering mirrors, G1-G4: Reflecting VBGs, D: Detector or beam dump

There are here 5 channels separated spectrally with step 0.5 nm with using VBG, in the particular setup it was achieved combining efficiency >93% and total power >750W. To improve the performance of this combining approach and achieve higher efficiency and total power it is necessary to overcome the resulting beam quality degradation due to heating effects happening in the VBG.

It is known that when high power beams are used with gratings, they can heat the gratings causing focusing and distortion of the beam, hurting beam quality. According to the theoretical considerations presented in paper[1], Fig. 2, the parameters of a resulting beam can be drastically improved when the combined laser beams have super-Gaussian intensity distribution, this allows both reduce the phase distortion effects due to heating the VBG and provide acceptable M^2 parameter of resulting beam after combining. Here results of mathematical modeling demonstrate comparison of parameter M^2 of Gaussian and super-Gaussian beams of the

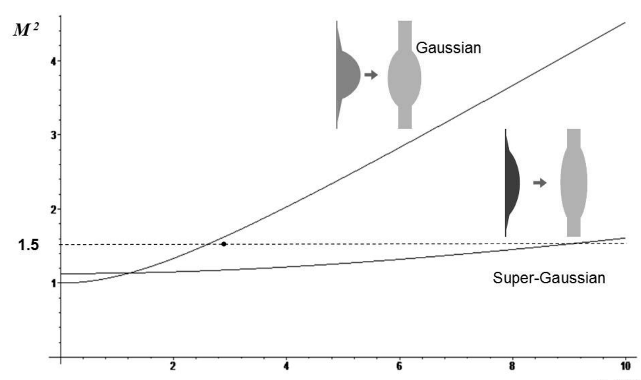

Figure 2 Dependence of M^2 of the Beams on Absorption

same power propagating through the same optical element. In case of super-Gaussian beam due to flatness of phase distortion profile and smaller intensity in the center the M^2 grows much slower than M^2 for Gaussian beam despite initial slightly higher value of M^2 of undistorted super-Gaussian beam. Horizontal coordinate has values of normalized power. One can see that for $M^2 = 1.5$ the super-Gaussian beam has more than 3 times advantage over the Gaussian beam.
In other words, changing the intensity profile from Gaussian to flattop or super-Gaussian one allows optimizing the conditions of SBC technique itself.

It is suggested to vary the intensity profile of a laser beam with using refractive field mapping beam shapers *πShaper* capable to provide various intensity distributions, in the layout on Fig. 1 the *πShaper* to be located right after the collimator of fiber laser. The design principles of refractive beam shapers of the field mapping type are well-known and described in the literature[3,4,5]. These beam shapers have two optical components and transform the laser beam profile in a controlled manner, by accurate inducing of wave aberration by the first component and further its compensation by the second one, Fig.3, top. The resulting collimated output beam has a uniform intensity and flat wave front. It also has low divergence - comparable to that of the input beam. In other words, the field mapping beam shapers, like *πShaper*, transform the beam profile without deterioration of the beam consistency and without increasing its divergence.
For the purpose of further considerations let us summarize main optical features of *πShaper* systems being used in this work:

- refractive optical systems transforming Gaussian, or close to Gaussian intensity distribution of source laser beam to a flattop (or top-hat, or uniform) one;
- transformation is realized through the phase profile manipulation in a controlled manner - accurate inducing by the first component of spherical aberrations to achieve the energy re-distribution and further compensation of the aberration by the second optical component;
- the output beam is free of aberration, the phase profile is maintained flat and low beam divergence is provided;
- TEM_{00} or multimode beams applied;
- collimated output beam,
- the resulting beam profile is kept stable over large distance;
- achromatic optical design, hence the beam shaping effect is provided for a certain spectral range simultaneously;
- Galilean design, no internal focusing.

Example of beam shaping for Nd:YAG laser with using *πShaper* is presented in Fig.4.

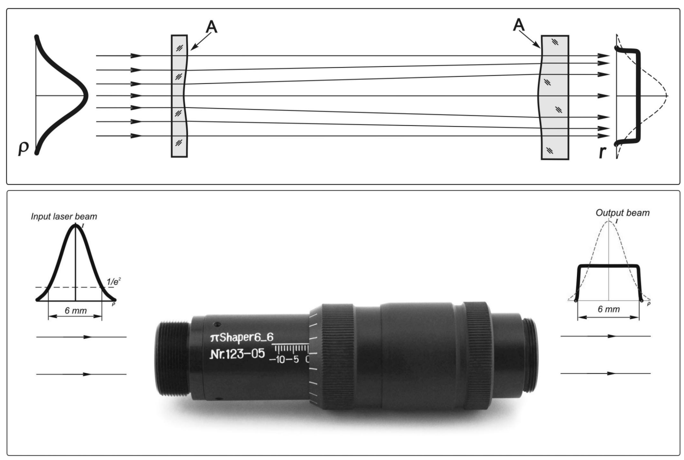

Figure 3 Refractive field mapping beam shaper *πShaper*

The experimental data of measured profiles show that the *πShaper* not only converts the intensity profile but improves also the spot shape – one can see the slightly distorted input beam is transformed to a flattop output beam with regular round spot.

One more important feature of the refractive field mapping beam shapers is that their operational principle presumes the input beam has a certain size (usually defined as diameter at $1/e^2$ intensity level) and a certain intensity profile (Gaussian or similar profiles with peak intensity in the centre). If an input beam size deviates from the pre-determined one the resulting profile varies as well. In other words, *a variation of input beam size corresponds to variation of output beam intensity distribution, and the size of the output beam stays almost invariable*. For example, when a *πShaper* is intended to convert the Gaussian beam to the flattop one and the input beam is essentially smaller, say 2-3 times less than a specified value, the beam shaper operates as an ordinary beam-expander and the resulting profile stays almost the same like at the entrance i.e. Gaussian. This effect is discussed thoroughly in paper[6] and is demonstrated in Fig. 5 where results of theoretical calculations as well as measured in real experiments beam profiles are shown. The data relate to the *πShaper 6_6* which design presumes that a perfect

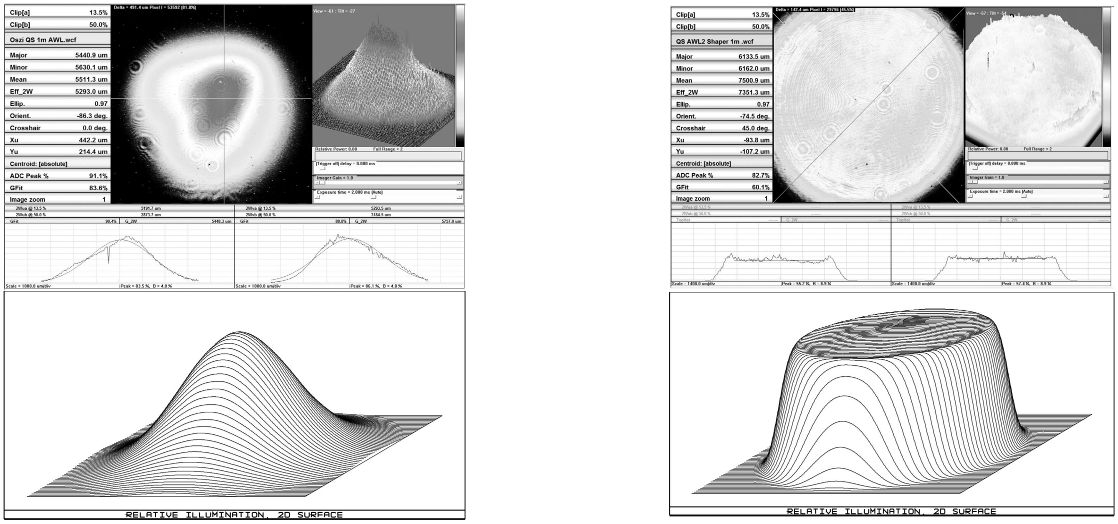

Figure 4 Beam shaping with *πShaper*: Left – Input TEM_{00} beam, Right - after the *πShaper*

(Courtesy of InnoLas Laser GmbH)

Gaussian beam with $1/e^2$ diameter 6 mm to be converted to a beam with uniform intensity (flattop) with FWHM diameter 6.2 mm. When the input beam has a proper size, Fig.5 a), the resulting beam profile is flattop, Fig.5 b). But change of input beam size results in changing of the output beam profile: increasing of diameter leads to downing of intensity in the beam centre, Fig.5 c), sometimes this distribution is called "inverse Gauss"; beams size reduction allows to get a convex profile that approximately can be described by super Gauss functions, Fig.5 d), just this profile is of great importance for the SBC technique.

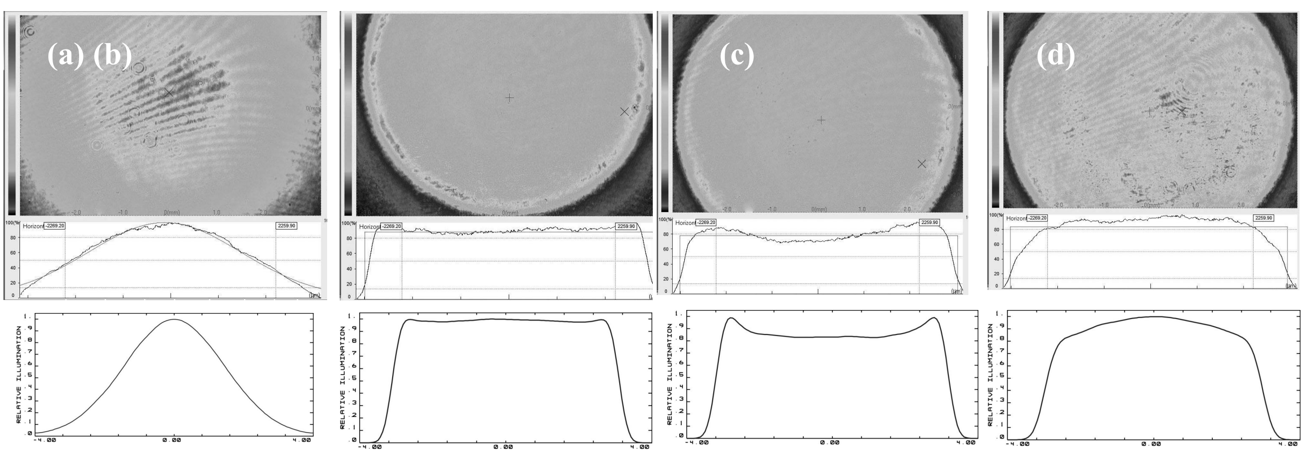

Figure 5 Experimental and theoretical intensity profiles:

a) TEM_{00} Input beam, D_{in} = 6 mm ($1/e^2$), b) Flattop output profile when by D_{in} = 6 mm ($1/e^2$) ,

c) Concave output profile ("Inverse Gauss"), D_{in} = 6,5 mm ($1/e^2$) d) Convex output profile ("superGauss"), D_{in} = 5,5 mm ($1/e^2$)

Courtesy of IPG Photonics)

Evidently, a simple variation of laser beam size allows to generate various profiles and this can be done on with the same beam shaper. To vary the beam diameter the ordinary beam expanders, can be applied. With using a zoom beam-expander one can steady vary the resulting beam profile and provide super-Gauss distribution being optimum for the spectral beam combining with using VBG.

3. EXPERIMENTAL WORK

In order to prove the theoretical conclusions the experimental setup according to the layout on Fig. 6 was built. For current experiments with *πShaper* it was used a VBG with identical parameters to low absorbing gratings which we used in experiments with high power high spectral density beam combining[1]. Absorption of this grating was increased in 165 times up to $3.3*10^{-2}$ cm^{-1} by an additional UV exposure. In that way we could model VBG thermal behaviour in 150 W beam which were equal to 25 kW normalized power from point of view of thermal effects in a system with a low absorbing VBG.

In the experimental setup a high power beam passed through a VBG and heated it. Average temperature grown up to 109-123°C in the region illuminated by a high power beam with 8.2 kW normalized power. This result was obtained by measurement of a shift of a Bragg wavelength position under illumination of the VBG by a superluminescence diode in transmitting geometry under an incident angle close to normal. We compared difference in optical distortions which appeared in the VBG due to heating by Gaussian or flat top beam produced by the *πShaper* at different normalized power levels. Both beams had 6.2 mm beam diameter on the level of $1/e^2$.

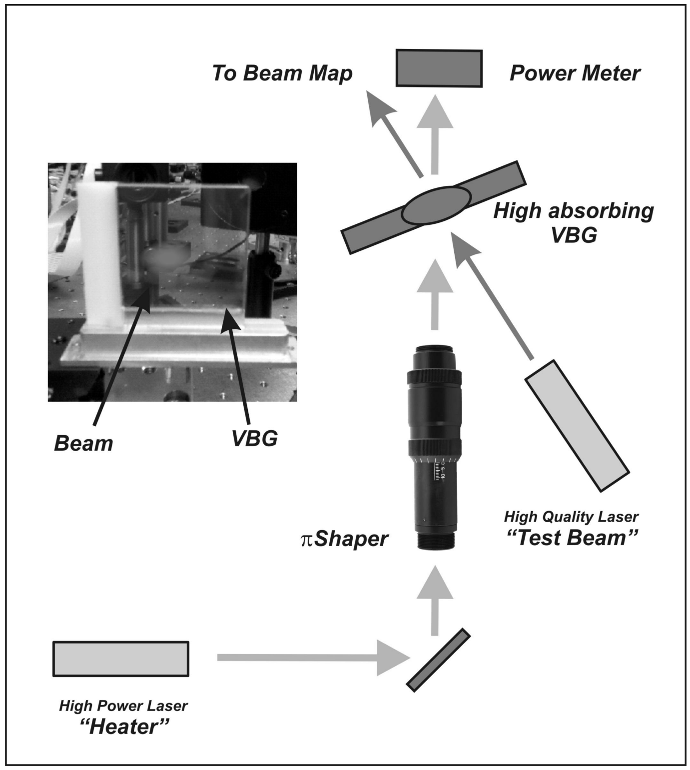

Figure 6 Experimental setup

To characterize these distortions we measured M^2 of a test high quality beam with 6.5 mm diameter. The beam from a tunable laser was applied as a test beam in transmitting and reflecting geometry. It had M^2=1.05 and allowed clearly observing beam distortion due to thermal lensing in the VBG. In transmitting geometry we detuned wavelength of the test beam from a Bragg wavelength for 7 nm and thermal shift of Bragg wavelength did not influence our data. In reflecting geometry we tuned wavelength of the testing laser to compensate temperature shift of Bragg wavelength by heating of high power laser and achieved maximum reflectivity from grating.

Some experimental results with high order super-Gaussian beam (almost flattop intensity profile) are shown on the chart in Fig. 7. A significant decrease of optical distortion in an optically heated VBG was observed for a flattop beam in comparison with a Gaussian beam. M^2 is differed 1.5 times when the VBG heated by flat top and Gaussian beams. As theory predicted, the paper[1], a flattop or super-Gauss high power beam introduces lower optical thermal distortion in comparison with a Gaussian beam. One can see correspondence of these measurement data with the results of theoretical calculations presented in Fig. 2.

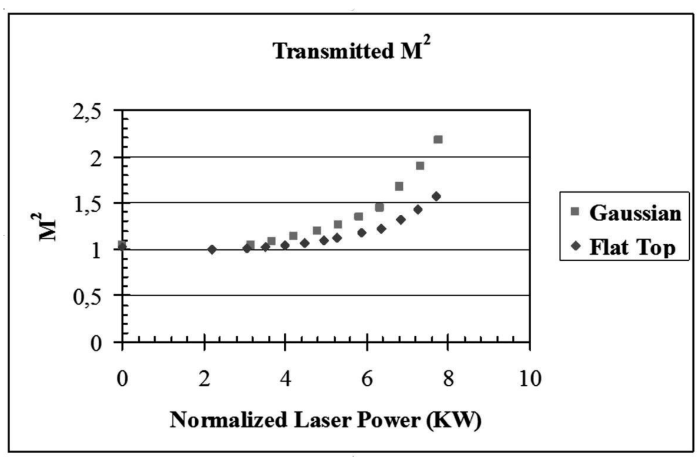

Figure 7 Comparison of measurement results

4. CONCLUSION

Performance of spectral beam combining (SBC) technique realized with using volume Bragg gratings can be drastically improved when the intensity distribution of the beams to be combined is transformed from Gaussian to super-Gaussian or flattop one. This transformation can be provided by refractive beam shapers of field mapping type, for example *πShaper*, having specific features being important just for this combining technique: variable beam shaping, so the flattop, inverse Gauss and super-Gauss profiles can be provided with the same *πShaper* unit, conserving the beam consistency, theoretically zero wave aberration high resistance to powerful laser radiation, etc. Results of experimental researches are in good correspondence with theoretical prediction about improving the SBC technique by the beam shaping and providing acceptable quality of a combined beam in far field. It is important also to mention that this beam shaping approach can be applied to other problems related to high-power beam propagation through absorbing optical elements.

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