Strong reducing of the laser focal volume

Thomas Godin[a], Sandile Ngcobo[b], Emmanuel Cagniot[a], Michael Fromager[a], Andrew Forbes[b], Kamel Aït-Ameur*[a]

[a] Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA-CNRS-ENSICAEN-Université de Caen, 6 Bd Maréchal Juin, 14050 Caen cedex 4, France;

[b] CSIR National Laser Centre, PO Box 395, Pretoria 0001, South Africa

ABSTRACT

Many applications of lasers seek nowadays for focal spots whose corresponding volume is getting smaller and smaller in order to ensure high spatial resolution. This problem, studied by many research groups around the world, is the core of this research work which deals with controlling the focal volume of a focused laser beam. Indeed, our objective is to develop a new method based on spatial treatment of laser beams, allowing to solve, in an original and efficient manner, two fundamental issues that have not been treated satisfactorily yet, i.e. :

(i) The generation of a special laser beam, which has the ability to produce a focal volume smaller than the one resulting from a more common Gaussian beam, when focused by an ordinary lens. The expected reduction factor of the focal volume is in the order of several hundreds, when the existing methods do not exceed few tenths.

(ii) The decoupling between transversal and longitudinal resolutions within the focal volume, contrary to Gaussian beams whose depth of field is proportional to the square of its beam-waist radius. The method that it is developed is based on two steps: First, the laser is forced to oscillate on a high-order but single transversal mode TEM_{p0}, which is secondly spatially beam-shaped thanks a proper Diffractive Optical Element (DOE) that allocates the super-resolution feature².

Keywords: laser beam shaping, transverse modes, super-resolution, focal volume

1. INTRODUCTION

Many laser applications are based on their beam focalisation, thus, their spatial resolution is directly related to the focal spot volume, as in the case of:

- 3-D laser prototyping involving photo-polymerization by two-photon absorption [1-3]
- Linear and non-linear fluorescence microscopy [4,5]
- Optical tweezers [6,7]
- Direct writing lithography [8]

Those applications, as many others, are based on the focalisation of a laser beam, which is at best Gaussian-shaped, or in other words, described by a M^2 factor equal to 1, meaning that the beam is diffraction-limited. When $M^2 > 1$, the beam is said « M^2 times diffraction-limited ». The latter case is generally considered uninteresting since the beam brightness, i.e., its ability to produce high intensities while characterized by a high Rayleigh distance or depth of field, is reduced. It is worth noting that $M^2 > 1$ does not necessarily mean a low spatial coherence, especially for single high-order transversal modes. In this paper we will show, contrary to established views, how spatially coherent laser beams having a high M^2 factor can be of high interest.

Before to proceed, it can be worth to remind that the geometry of the focal spot resulting from a focussed Gaussian beam is described by two related lengths:

(i) The first one, transversal, is the beam-waist width, W_0

(ii) The other, longitudinal, corresponds to the Rayleigh distance or depth of field, and is proportional to the transversal length: $Z_R = (\pi W_0^2)/\lambda$.

* kamel.aitameur@ensicaen.fr

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In addition, we can define the focal volume for a Gaussian beam V_G :

$$V_G = \int_{-Z_R}^{+Z_R} S(Z)dZ = \frac{\pi^2 W_0^4}{\lambda}, \qquad (1)$$

where $S(Z)$ is the Gaussian beam section.

Let us consider a simple focalisation geometry that can be found in most of the applications. A collimated Gaussian beam (width W) is incident onto a converging lens (focal length f). The latter transforms it into another Gaussian beam whose beam-waist W_0 is located at the focal plane:

$$W_0 \approx \frac{\lambda f}{\pi W}. \qquad (2)$$

It has to be noted that Eq. (2) is only valid for incident beams having a Rayleigh Distance ($\pi W^2 / \lambda$) much longer than the focal length f. From Eq. (1) and (2), it is then clear that a spatial resolution improvement requires a smaller W_0. For this purpose, f has to be reduced or the incident beam width W has to be increased. However, focal length f cannot be decreased indefinitely, especially because the lens diameter would decrease accordingly, requiring a small W to avoid beam truncation. Thus, it is important to note that equation (2) describes the diffraction limit for a given Gaussian beam.
Historically, spatial resolution in most of laser applications has been limited by the Rayleigh criterion. To go beyond the diffraction limit, either by focusing a coherent light, or by observing an object lighted by a coherent light, is nowadays a subject under strong investigations. Before to proceed, it is important to precise the sense of the term "***super-resolution***". It usually relates to the focusing of light into a spot having dimensions smaller than the diffraction limit or to the use of a particular refinement that allows the spatial resolution improvement of the device under consideration. For instance, several techniques have been developed for improving the microscopy resolution, either with near-field optics, where a variety of plasmonic nano-antennas have the ability to concentrate light into a volume much smaller than that derived from the diffraction limit, or with far-field schemes, by optical patterning of the excitation (4-Pi confocal microscopy, I5M microscopy and stimulated emission depletion microscopy STED), or by single-molecule imaging (photoactivation localization microscopy, stochastic optical reconstruction microscopy, etc.). However, all of these "super-resolution" techniques have been developed for one application only, and cannot usually handle high powers, preventing them to improve spatial resolution of applications such as 3D laser prototyping and direct writing lithography for instance. In this project, we proposed to develop a new concept, based on laser beam shaping which should produce beams able to generate focal spots having a small volume in comparison with that imposed by the diffraction limit. This new method, capable of concentrating high power within the focal volume, is much more "general" and could then be applied to different applications such as 3-D laser prototyping, linear and non-linear fluorescence microscopy, nano-structuration of materials, optical tweezers, optical tomography… in order to improve their spatial resolution. In addition, it is important to remind that our approach can be used in combination with non-linear phenomena (2-photon absorption, etc.) to further improve recent technologies aiming already for spatial resolution enhancement. In this framework, we will demonstrate that our concept of super-resolution is much more efficient than the existing methods which are reviewed below.

The use of radially polarised laser beams allow also to generate in the focal plane a non-propagative field component having a lateral width smaller than the diffraction limit [9-12]. The difficulty for applying this solution has its origin in both the complexity in forcing the laser polarisation to be radial [13-15] and in the suppression of the additional transversal linear polarisation responsible for a spot larger than the diffraction limit [11].

The generation of a focal spot having a size smaller than that of a Gaussian beam can be achieved from the axial superposition of two Gaussian beams orthogonally polarised with their beam-waist planes shifted. Since the Gouy phase difference associated with the two beams exits only in the vicinity of the focal plane, it results a polarisation component having the property of super-resolution which improves longitudinal and transversal resolutions with a rate of about 30% [16]. Nevertheless, the improvement factor of the focal volume is weak since it is only equal to three.

Another possibility for getting super-resolution in a focal spot is to set, in front of the focusing lens, an absorbing ring [17], or a system of annular dephasing zones [18-20]. The main drawback of these methods is that the shrinking of the central spot, in the focal plane, is done to the detriment of the surrounding rings which show their energy increasing [21].

The optical Kerr effect can generate super-resolution since the self-diffraction occurring in a Kerr medium can lead to super-resolution which can reduce by 30% the size of the focal spot [22].

2. TRANSFORMATION OF A TEM_{P0} BEAM INTO A SINGLE-LOBED BEAM

For laser applications that need a small focal volume, one can imagine the characteristics of the ***ideal laser beam***. The latter, when focused, should give rise to a spot having a width smaller than that of a Gaussian beam, and a depth of field shorter than that of a Gaussian beam having the same beam-waist size. Considering that, in the general case, the depth of focus (Rayleigh distance) of a laser beam expresses as

$$Z_R = \frac{\pi W_0^2}{\lambda M^2}, \tag{3}$$

then we can deduce the properties of the ideal laser beam mentioned above. It should be a laser beam having a poor quality ($M^2 >> 1$) but giving rise to a single lobed pattern, in the focal plane of a focusing lens, which has the property of super-resolution. The latter means that the width W_f of the focused "ideal laser beam" is smaller than the width W_0 of the focused Gaussian beam which should be observed from a Gaussian beam of equivalent width, focused with the same lens. The objective of this work is to demonstrate the possibility to produce such "ideal laser beams" allowing to improve significantly the spatial resolution of a certain number of laser applications such as non-linear microscopy, optical trapping and tweezing, 3-D prototyping…

Let us consider a collimated symmetrical Laguerre-Gauss TEM_{p0} beam of order p and width W which is made up of a central peak surrounded by p rings of light (Fig.1).

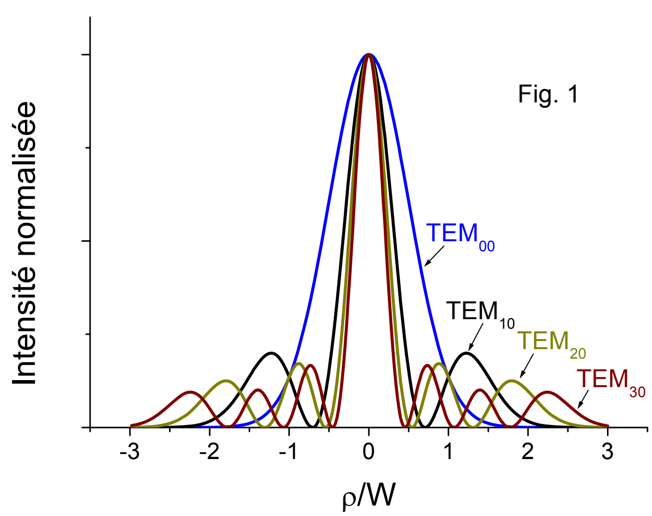

Figure 1. Radial intensity distribution of the four-first symmetrical Laguerre-Gauss TEM_{p0} beams.

It is worth noting that using focused TEM_{p0} beams in the hope to reduce the focal volume is awkward since the latter increases as $(2p+1)V_G$. In fact, our idea is to transform a TEM_{p0} beam having a propagation factor $M_p^2 = (2p+1)$, into a single-lobed pattern of width W_f in the focal plane of a focusing lens. A Diffractive Optical Element (DOE) is considered for this reshaping operation in order to convert the alternately out-of-phase rings of the TEM_{p0} beam into a unified phase (Fig.2). The function realised by the DOE is a "rectification" of the wavefront.

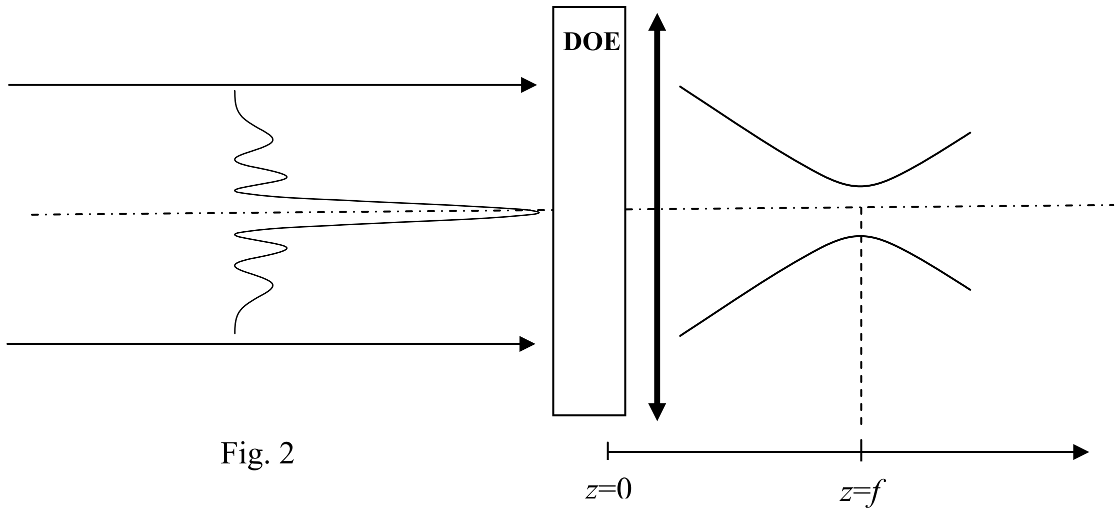

Fig. 2

Figure 2. Schematic optical layout for investigating the laser beam tailoring ability of a binary Diffractive Optical Element having a transmittance alternately equal to -1 or +1 modeled on the p light rings of the incident TEM_{p0} beam.

The transformation quality of a TEM_{30} beam into a single-lobed pattern in the focal plane is shown in Fig. 3. It is clear that the intensity pattern of the rectified beam is sharper than that of the focused TEM_{00} and TEM_{30} beams. The calculation are made for λ=1064nm, W=1mm and f=50mm

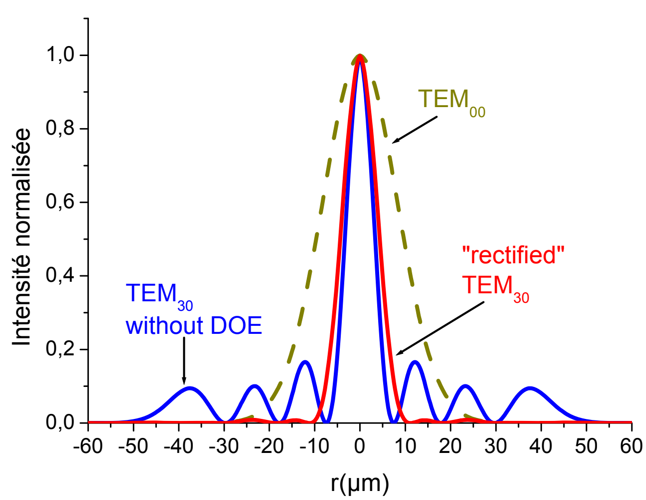

Figure 3. Normalised intensity at the focal plane: TEM_{00} without DOE (Dashed dark yellow), TEM_{30} without DOE (blue solid line), rectified TEM_{30} (red solid line)

Fig. 3 shows that focusing a rectified TEM_{30} beam instead of a Gaussian TEM_{00} beam allows the focal spot size to be reduced by a factor of 2.2, although using the same focusing lens. This is a **super-resolution** effect, and the DOE achieves an efficient transfer of power from the surrounding rings of the TEM_{p0} beam toward the central peak of the rectified beam. The efficiency of the beam reshaping can be measured by comparing the power content α_R in the central peak of the rectified TEM_{p0} beam with the power content α_{LG} in the central peak of a pure TEM_{p0} beam. The result is shown in table 1, and it is seen that ratio α_R / α_{LG} varies from about 3 to 10 when order p varies from 1 to 5.

p	α_{LG} (%)	α_R (%)
1	26.4	82.6
2	15.6	78.5
3	11.2	76.3
4	8.6	74.6
5	7	73.8

Table 1: Power content α_R (α_{LG}) in the central peak of a focused rectified (pure) Laguerre-Gauss beam TEM_{p0} for p varying from 1 to 5.

As a consequence, the transformation of a TEM_{p0} beam into a single-lobed pattern is done with a good efficiency. Now, it remains to characterise the reshaped beam by its beam propagation factor M^2 and the width W_f of the focal spot. The result is given in table 2.

Incident beam	W_f (µm)	η	M^2
TEM_{00} without EOD	16.5	1	1
TEM_{10}	10.6	17	2.9
TEM_{20}	8.5	68	4.8
TEM_{30}	7.3	172	6.6
TEM_{40}	6.4	366	8.5
TEM_{50}	5.8	675	10.3

Table 2: Width W_f and beam propagation factor M^2 of the focussed rectified TEM_{p0}. The ratio $\eta = V_G/V_R$ represents the reduction factor of the focal volume.

It is seen that $M^2 \approx M_p^2$, which is not surprising considering the work of A.E. Siegman [23] who has demonstrated that binary optics cannot improve the beam propagation factor. In our case, this property is useful in order to adjust the depth of field of the rectified TEM_{p0}, which is M^2 times smaller than that of a Gaussian beam having a beam-waist of width W_f. This property is essential since it allows the decoupling of longitudinal and transversal resolutions. Indeed, depending on the envisaged application, one can consequently produce beams having, for a given W_f, different depths of field $Z_R^{'}$ which can be adjusted by setting the value of *p,* i.e., the order of the incident TEM_{p0} beam :

$$Z_R^{'} = \frac{\pi W_f^2}{\lambda(2p+1)}, \tag{4}$$

It can be noted that this property is distinct from the super-resolution. One can observe in table 2 that the width W_f of the focused rectified TEM_{p0} is smaller, whatever *p* is, than that of the Gaussian TEM_{00} beam focused by the same lens without any DOE. It is worth noting that the width W_f of the Gaussian beam, equal to 16.5µm, also corresponds to $W_0 = \lambda f / (\pi W)$, i.e. the value of the beam waist given by the *ABCD* law. Obtaining $W_f < W_0$ is then a super-resolution effect since the obtained focal spot size is smaller than the diffraction limit expressed in Eq. (2). The factor of reduction of the focal spot size is about 280%, for the rectified TEM_{50} while it does not exceed 30% to 40% for the existing methods.

Finally, the achieved performance of the focal volume reduction by rectification of a TEM_{p0} beam can be summarised through the following factor:

$$\eta = V_G / V_R, \tag{5}$$

where $V_R = (\pi^2 W_f^4)/(\lambda M^2)$ is the focal volume associated with the focused rectified beam. The results are given in Table 2. It is seen that ratio η increases with mode order *p* and is equal to 675 for *p*=5. Then, an increase of the transverse and longitudinal resolutions by a factor of $(675)^{1/3} \approx 8.7$ can be expected, which is very promising for the improvement of spatial resolution of 3-D laser prototyping and non-linear microscopy, and other laser applications such as lithography, cutting and writing.

3. CONCLUSION

We have demonstrated that the oscillation of a laser on a high-order but single transverse mode can be very useful. Indeed, a symmetrical Laguerre-Gauss mode TEM_{p0} can generate focal volume reduction if it is rectified by an adequate Diffractive Optical Element. The factor by which the focal volume is reduced can be as high as 675 for a mode order *p*=5. In this case, one can expect an increase of the transverse and longitudinal resolutions by a factor of about $(675)^{1/3} \approx 8.7$. These results are very promising for the improvement of spatial resolution of 3-D laser prototyping and non-linear microscopy, and other laser applications as lithography, cutting and writing.

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REFERENCES

[1] R. Infuehr et al, " Functional polymers by two-photon 3D lithography", Appl. Surf. Sciences, **254**,836-840 (2007).
[2] W.H. Teh et al, "SU-8 for real three-dimensional subdiffraction-limit two-photon microfabrication", Appl. Phys. Lett., **84,** 4095-4097 (2004).

[3] K.S. Lee, R.H. Kim, D.Y. Yang, S.H. Park, “Advances in 3D nano/microfabrication using two-photon initiated polymerization”, Prog. Polym. Sci., **33,** 631-681 (2008).
[4] W. Denk, J.H. Strickler, W.W. Webb, “2-photon laser scanning fluorescence microscopy”, Sciences, **248,** 73-76 (1990).
[5] W.R. Zipfel, R.M. Williams, W.W. Webb, “Nonlinear magic: multiphoton microscopy in the biosciences”, Nature Biotechnology, **21,** 1368-1376 (2003).
[6] A. Ashkin, J.M. Dziedzic, T. Yamane, “Optical trapping and manipulation of single cells using infrared laser beams”, Nature, **330,** 769-771 (1987).
[7] J.R. Moffit, Y.R. Chemla, S.B. Smith, C. Bustamante, “Recent advances in optical tweezers”, Annu. Rev. Biochem., **77,** 205-228 (2008).
[8] J. Wei, J. Liu, X. Jiao, “ Subwavelength direct laser writing by strong optical nonlinear absorption and melt-ablation threshold characteristics”, Appl. Phys. Lett., 95, 241105 (2009).
[9] K.S. Youngsworth and T.G. Brown, “Focusing of a high numerical aperture cylindrical vector beams”, Opt. Express, **7,** 77-87 (2000).
[10] Q. Zhan and J.R. Leger, “Focus shaping using cylindrical vector beams”, Opt. Express, **10,** 324-331 (2002).
[11] S. Quabis, R. Dorn, M. Eberler, O. Glöckl, G. Leucs, “Focusing light into a tighter spot“, Opt. Commun., **179,** 1-7 (2000).
[12] H. Wang, L. Shi, B. Lukyanchuk, C. Sheppard, C.T. Chong, “Creation of a needle of longitudinally polarized light in vacuum using binary optics”, Nature Photonics, **2,** 501-505 (2008).
[13] N. Passilly, R. de Saint Denis, K. Aït-Ameur, F. Treussart, R. Hierle, J.-F. Roch, « Simple interferometric technique for generation of a radially polarized light beam », J. Opt. Soc .Am. A, **22,** 984-991 (2005).
[14] M. Bashkansky, D. Park, F. K. Fatemi, “Azimuthally and radially polarized light with a nematic SLM”, Opt. Express, **18,** 212-217 (2010).
[15] M.S. Roth, E.W. Wyss, H. Glur, H.P. Weber, “Generation of radially polarized beams in a Nd:YAG laser with self-adaptative overcompensation of the thermal lens”, Opt. Lett., **30,** 1665-1667 (2005).
[16] J.B. Steward, B.E.A. Saleh, M.C. Teich, J.T. Fourkas, “ Experimental demonstration of polarization-assisted transverse and axial optical superresolution”, Opt. Commun., **241,** 315-319 (2004).
[17] V. Paeder, T. Scharf, P. Ruffieux, H.-P. Herzig, R. Voelkel, K.J. Weible, “Microlenses with annular amplitude and phase masks”, J. Eur. Opt. Soc. Rapid com., 2, 07005 (2007).
[18] D.M. de Juana, V.F. Canales, P.J. Valle, M.P. Cagigal, “ Focusing properties of annular binary phase filters”, Opt. Commun., 229, 71-77 (2004).
[19] S.F. Pereira, A.S. van de Nes, “Superresolution by means of polarisation, phase and amplitude masks”, Opt. Commun., **234,** 119-124 (2004).
[20] T.G. Jabbour, M. Petrovitch, S.M. Kuebler, “Design of axially super-resolving phase filters using the method of generalized projections”, Opt. Commun., 281, 2002-2011 (2008).
[21] C.R.J. Sheppard, “Fundamentals of supperresolution”, Micron, **38,** 165-169 (2007).
[22] J. Wei, M. Xiao, “The origin of the super-resolution vian nonlinear thin film”, Opt. Commun., 281, 1654-1661 (2008).
[23] A.E. Siegman, “Binary phase plate cannot improve laser beam quality”, Opt. Lett., **18,** 675-677 (1993).