INTRODUCTION TO STRUCTURED LASER BEAM FOR ALIGNMENT AND STATUS OF THE R&D

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Abstract

A new method of generating a Structured Laser Beam (SLB) has been proposed recently. The SLB is a pseudo-non-diffractive optical beam. Its transverse optical intensity profile looks similar to that of a quasi Bessel beam and shows a narrow central core of high intensity surrounded by concentric circles. The SLB has the ability to propagate over very long distances, theoretically to infinity with a low divergence of the central core beam. It has been tested up to 200 m and during the experiments a divergence of typically 0.01 mrad has been measured, the diameter of the central spot at start being about 0.01 mm. The SLB properties open potential applications in different domains, comprising geodetic and large scale metrology. Even if the SLB is still at a research stage it appears as a promising candidate for the development of optical long range reference lines for alignment systems. This article is an introduction to the SLB, to its generation principle and to some of its characteristics, in particular the ones interesting for alignment. It relates the status of some aspects of the on-going research. It summarizes some SLB study results, among them the creation of SLBs at long distances, the study and simulations of beam straightness, or the creation of SLB with non-classical polarization.

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INTRODUCTION

A new method of generating a Structured Laser Beam (SLB) has been proposed recently [1]. The SLB is a pseudo-non-diffractive optical beam having a transverse optical intensity profile looking similar to that of a quasi Bessel Beam (BB). As this last, SLB shows a high intensity narrow central core surrounded by concentric circles. BB have been used for alignment purposes [2-3-4], but the fact that their length does not exceed 20 m under standard conditions is a limiting factor for their use in long-range. The SLB has the ability to propagate over very long distances, theoretically to infinity, with a low divergence of the central core beam. The SLB properties open potential applications in different domains, comprising geodetic and large scale metrology.

In this paper, an introduction to the SLB is given, as well as a description of some of its characteristics and properties. Some aspects and study results are also highlighted.

SLB INTENSITY DISTRIBUTION IN THE TRANSVERSE PLANE

The SLB is characterized by its transverse profile, which is similar to a BB. It has a narrow and intense central core surrounded by dark and intense concentric circles, see Figure 1. The core itself can then be strictly bounded by a dark circle whose intensity can be equal to zero if the elements of the SLB generator are correctly set.

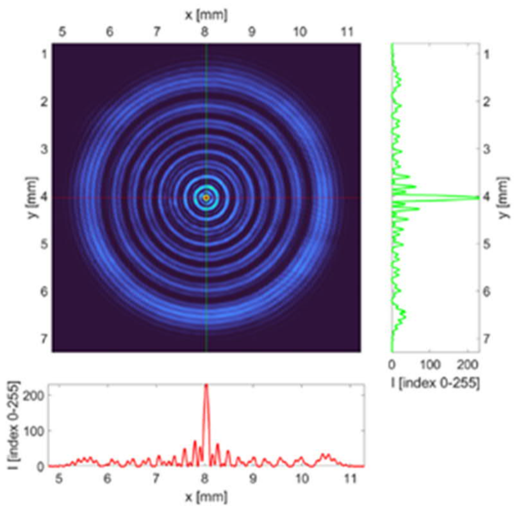

Figure 1: Example of the transverse intensity distribution of a real SLB

SLB GENERATION PRINCIPLE

Wavefront shape and SLB generation principle

The SLB is the result of the superposition of the waves coming from a wavefront having a special shape, as illustrated in Figure 2, obtained after the spherical aberration produced by the generation system. This phenomenon produces an SLB with a high intensity central core surrounded by high and low intensity rings.

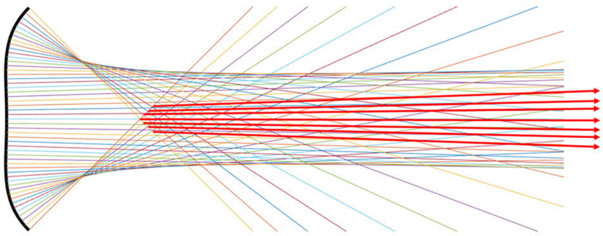

Figure 2: Example of wavefront longitudinal cross section and ray tracing after the generator, and illustration of the created SLB represented by the red arrows.

Generator focussing and SLB profile

The SLB generator has the ability to be easily tuned in order to change the shape of the wavefront and consequently the transverse profile of the produced SLB as illustrated in Figure 3.

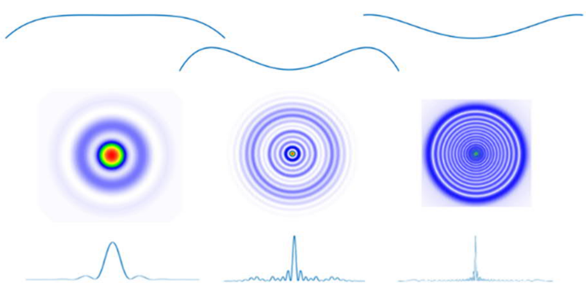

Figure 3: Example of intensity distribution on a SLB cross section according to the shape of the wavefront after the generator. For each of the 3 cases the wavefront is seen on top, the SLB intensity distribution in a cross section is given below, and an intensity profile is given at the bottom (not scaled).

When changing the generator focusing parameter the SLB is varying from a beam with a low number of visible rings, a low divergence of the full beam (including the rings), an intense central core with relatively high divergence to a beam with a high number of visible rings, a more diverging full beam (including the rings), a less intense central core with small divergence. This capability allows an optimisation of the SLB depending on the desired application.

SLB CORE DIVERGENCE

GB and SLB core diameter definition

There are several ways to characterize the diameter of a Gaussian beam. They are based on the definition of the diameter of an imaginary circle assuming a circularly symmetric. One of them is the Full Width at Half Maximum (FWHM) parameter defined as the diameter of an imaginary circle formed by the region in which the optical intensity reaches half the maximum value.

Another definition gives the GB radius (W) as the radial distance from the beam centre in the transverse plane where the intensity drops to $1/e^2$ times the intensity at the centre of the GB. 2W ~ 1.7.FWHM. See Figure 4. Note that this is the definition used in the text later.

The SLB transverse profile allows a different definition of its central core diameter. This one is based on the diameter of the real circle, so called Airy ring, with the 1st local minimum intensity and delimiting the SLB core as shown in Figure 5.

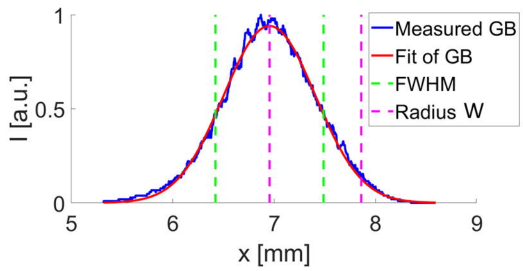

Figure 4: Visualization of a typical transverse profile from a measured GB, the GB diameter is given in this case by the Full Width at Half Maximum (FWHM)

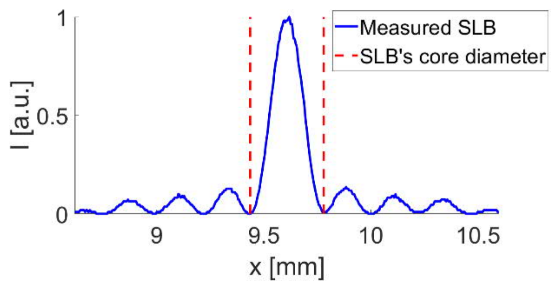

Figure 5: Visualization of a typical transverse profile from a measured SLB, the core diameter is given by the zero intensity of the first dark circle.

SLB divergence

SLB is subject to divergence, but the divergence of the central core is kept small along very long distances as shown on the simulation in Figure 6.

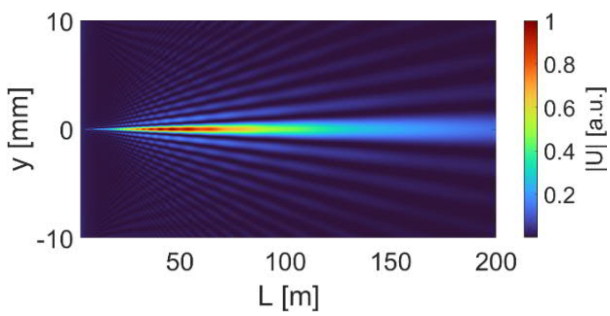

Figure 6: Longitudinal profile of the SLB field amplitude obtained from numerical simulations.

In the best result achieved so far, the beam shown in the Figure 7 was measured at a distance of 140 m from the generator. The diameter of the beam core is 1.3 mm. Knowing that the beam originated at a distance of 5 m from the generator with a diameter close to a few µm and that this diameter is almost linearly increasing with distance, the divergence of the central core beam is approximately 9.6 µrad.

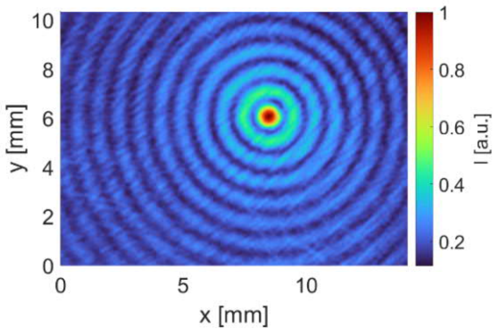

Figure 7: Image of the real SLB at a distance of 140 m from the generator. The optical intensity I is represented in arbitrary units.

Comparison with the Gaussian beam

A numerical model of a Gaussian beam from a laser source with a wavelength of 632.8 nm is considered on a 200 m long alignment window. The optimal GB keeping the lowest divergence along this 200 m has a waist in the centre of the alignment window. The radius of the GB in its waist is W_0. The longitudinal evolution of the GB radius can be described by the equation [5]:

$$W(z) = \sqrt{W_0^2 + \frac{z^2\lambda^2}{W_0^2\pi^2}}.$$

The effect of the square of the longitudinal coordinate z – originated at the waist position – in the equation indicates that the radius develops symmetrically on both sides. The relation shows that the function also depends on the radius of the GB at its waist W_0. By searching for the local minimum of this second dependence, the radius W_0 can be chosen in order to obtain the minimum GB radius W at a given z. In order to fulfil our conditions of low divergence for $z = +/-100$ m, the optimum radius at the waist is approximately $W_0 = 4.49$ mm, resulting in a radius of the GB at $z = +/-100$ m of approximately $W = 6.35$ mm This optimal GB is shown in the Figure 8.

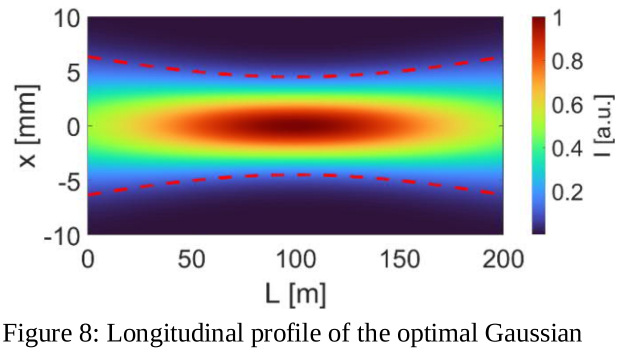

Figure 8: Longitudinal profile of the optimal Gaussian beam intensity. Dashed red curves indicate the radius of the GB.

Note that in order to avoid diffraction at the circular aperture, it is necessary to use a collimator imaging lens with an aperture diameter at least 6 times larger than the GB radius, so $D_{aper} \approx 38.1$ mm. If such a large projection lens is used for the SLB generation, it is possible to create a beam whose longitudinal profile is shown in Figure 6.

The contrasted and narrow profile of SLB is clearly more effective for accurately finding the centre position than the GB one, especially on long range.

SYMMETRY BREAK EFFECT ON SLB STRAITGHNESS

The SLB looks to be a promising candidate to create an optical reference line for the development of long distance alignment systems. The SLB straightness, in vacuum and independently of the propagation medium, which is the subject of another study, is of the main importance. In this frame, the symmetry breaking effect has to be carefully considered. Main causes of symmetry breaking can be due to the relative misalignment of the generator optical elements w.r.to the input beam axis, and to a non-symmetrical cropping of the beam in the propagation volume. Investigations for all cases have been conducted.

The research related to a symmetry breaking in the propagation volume can be found in [6]. It describes the effect on SLB straightness of a linear cropping on one hand (Figure 9) and of a circular symmetry breaking on the other hand (Figure 10). These phenomena have been studied in the Fresnel zone, the near zone close to the generator where the optical field shape is changing with the distance, and in the subsequent Fraunhofer zone, the far zone where the optical field is invariant in shape. For this purpose an optimized simulation tool has been used. Simulations over a 1000 m long range and over a more typical 200 m range have been performed, see an example in Figure 11.

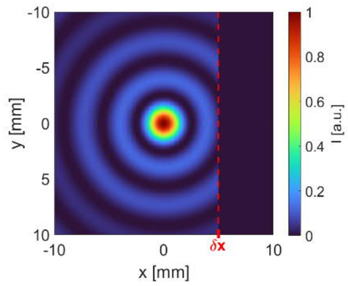

Figure 9: Linear cropping symmetry breaking of SLB.

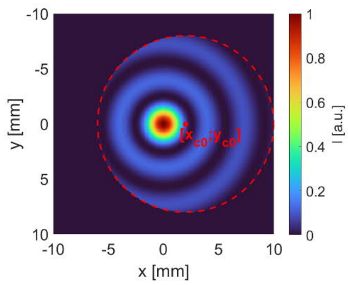

Figure 10: Circular symmetry breaking effect on SLB.

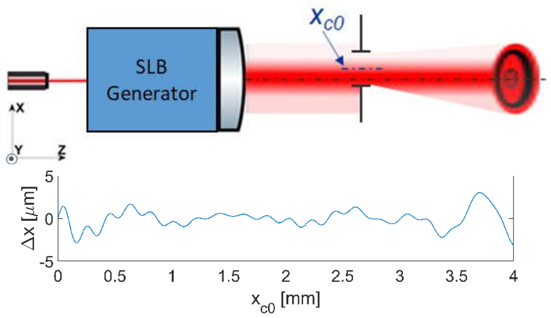

Figure 11: An example of SLB centre transverse position oscillation (Δx) at a distance of 200 m when moving a circular aperture of 40 mm diameter placed at 10 m from the generator. X_{c0} is the position of the aperture centre w.r.to the theoretical laser propagation axis.

The simulations show that, even if a symmetry breaking of the SLB in the transverse plane induces a modification of the beam centre position, this effect can be reduced at the micron level, even for long distances, by using optical element apertures and the propagation space surrounding the beam axis reasonably large.

SLB POLARIZATION

The polarization of the SLB strongly depends on the polarization of the input beam entering the generator. This subject is under study however some results and simulation have already been obtained. Components of the SLB polarization appear along each of the x, y and z axis depending on the location in the beam transverse plane and depending on the input beam polarization. Note that x axis and y axis are perpendicular and in the transverse plane of the beam, z axis is perpendicular to the xy plane along the beam axis and positive in the direction of the beam propagation.

Polarization distribution of an SLB generated from linearly polarized GB

Figure 12 to Figure 14 below show the electric filed (E) polarization components along x, y and z axis for a SLB generated from a GB with a linear polarization along x.

The x component of the polarization, Figure 12, appears everywhere in the bright zones and comes to zero in the dark circles. On the right side of the figure showing the real part of the complex amplitude value, one can see that the phase of the complex amplitude is the same along every bright circle.

The y component of the polarisation, Figure 13, is present in the bright circles except around the x and y axis and in the dark circles where y component of the polarization comes to zero. As visible in the right part of Figure 13 showing the complex amplitude real part, the complex amplitude in the (x<0; y<0) and in the (x>0; y>0) quadrants have the same phase and are in opposite phase with the one in the (x<0; y>0) and the (x>0; y<0) quadrants.

The z component of the polarisation, Figure 14, is present in the dark circles except around y axis and comes to zero gradually in the bright circles. As visible in the right part of Figure 14 showing the complex amplitude real part, the complex amplitude in the (x<0) and the (x>0) halves are in opposite phase.

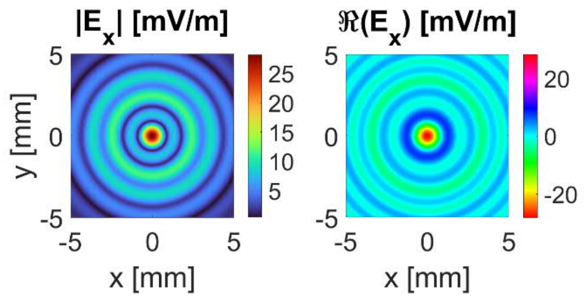

Figure 12: Component of the SLB polarization along x axis, the generator is illuminated with a GB linearly polarized along x. The colour scale represents the absolute value of the E field complex amplitude along x on the left and the real part of E complex amplitude along x at a given time on the right.

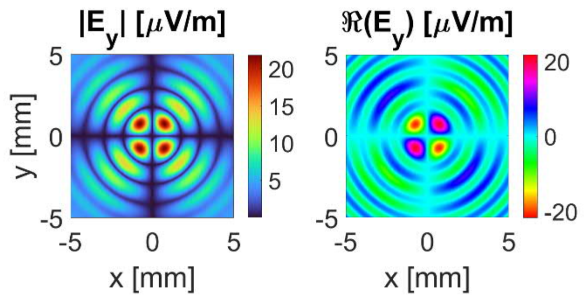

Figure 13: Component of the SLB polarization along y axis, the generator is illuminated with a GB linearly polarized along x. The colour scale represents the absolute value of the E field complex amplitude along y on the left and the real part of E complex amplitude along y at a given time on the right.

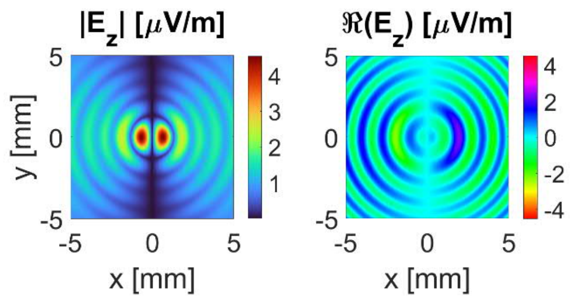

Figure 14: Component of the SLB polarization along z axis, the generator is illuminated with a GB linearly polarized along x. The colour scale represents the absolute value of the E field complex amplitude along z on the left and the real part of E complex amplitude along z at a given time on the right.

Polarization distribution of SLB generated with a circular polarization

For a SLB generated from a GB with a circular polarization, the x-component and the y-component appear everywhere in the bright zones and disappears in the dark circles. The simulations of the real part of the complex amplitude value with time show that the complex amplitude projected on x and y axis are in opposite phase.

The z-component of the polarization is distributed over the dark circles and decreases to become zero in the bright circles and at the centre (x=0; y=0). The simulations of the real part of the complex amplitude value show two nested helical shapes with the complex amplitude of each helix in opposite phase and decreasing with the distance to the centre. See Figure 15.

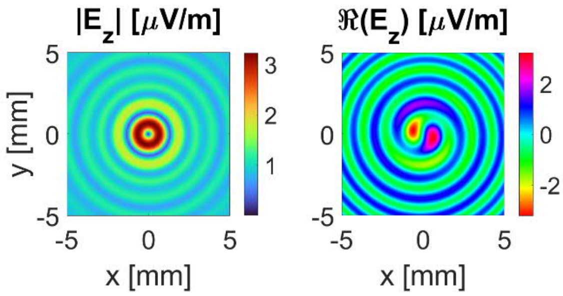

Figure 15: Component of the SLB polarization along z axis, the generator is illuminated with a GB with circular polarization. The colour scale represents the absolute value of the E field complex amplitude along z on the left and the real part of E complex amplitude along z at a given time on the right.

Polarization distribution of SLB generated with non-classical polarization

The study of the characteristics of SLB created with a non-classical polarization is on-going. In the next chapters, some of the results obtained with radial, azimuthal and intermediate states polarization are exposed.

Hollow Structured Beam creation

When generated from these types of non-classical polarization, a particular type of SLB is created so-called Hollow Structured Laser Beam (HSLB). HSLB transverse intensity distribution, at any distance from the generator, shows a dark central core surrounded by bright and dark circles. The Figure 16 shows a picture of a real HSLB created at CERN and which is in perfect agreement with the simulations.

As illustrated in Figure 17, the transverse profile of a HSLB is such that the intensity range is smaller than for a standard SLB. Note that this can ease the measurement of the beam intensity while remaining within the dynamic range of the imaging sensors.

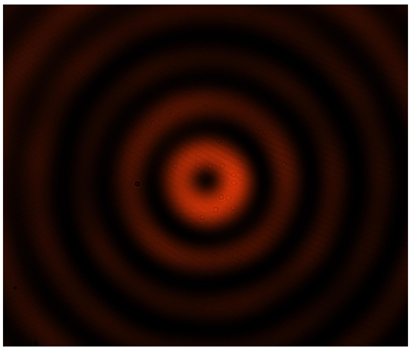

Figure 16: Image of the transverse intensity of a real HSLB created at CERN, zoom on the central part extracted from a full image.

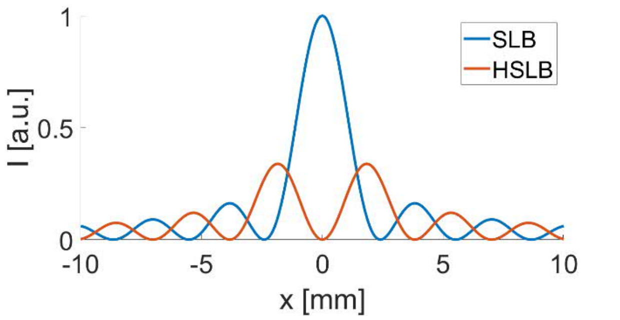

Figure 17: Transverse intensity profile of a standard SLB (blue curve with high intensity at x=0) and of a HSLB (red curve indicating 0 intensity at x=0).

Polarization distribution of structured laser beam generated from a radially polarized beam

In case of illumination of the generator with a radially polarized beam, the dark central core of the created Hollow SLB has a longitudinal polarization with electric field only and no magnetic field as shown in Figure 18.

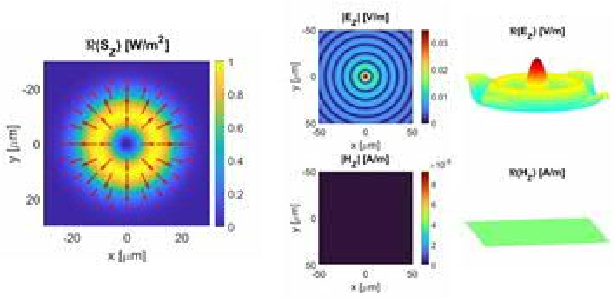

Figure 18: Hollow SLB created by feeding the generator with a radially polarized beam, see left part. The colour scale of the two plots at the centre represents the absolute value of the complex amplitude along z of the E field at top and magnetic field at bottom. On the right, the plots represent the real part of the complex amplitude along z for electric field, and for magnetic field, at a given time, respectively at top and at bottom.

Polarization distribution of structured laser beam generated from a beam with azimuthal polarization

When the illumination of the generator is done using a beam having an azimuthal polarization, the dark central core of the created Hollow SLB has a longitudinal polarization with magnetic field only and no electric field as shown in Figure 19.

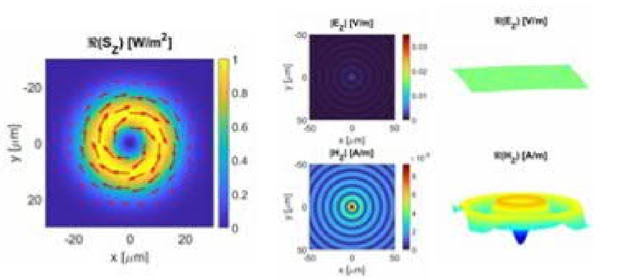

Figure 19: Hollow SLB created by feeding the generator with a beam with an azimuthal polarization, see left part. The colour scale of the two plots at the centre represents the absolute value of the complex amplitude along z of the E field at top and magnetic field at bottom. On the right, the plots represent the real part of the complex amplitude along z for electric field, and for the magnetic field, at a given time, respectively at top and at bottom.

Polarization distribution of structured laser beam generated from a beam with spiral polarization

When progressively changing the generator input beam polarization from only radial to only azimuthal, for all intermediate cases the generator is illuminated with a beam having spiral polarization. The created HSLB presents a longitudinal polarization in the dark central core with a mix of collinear electric and magnetic field. The ratio between electric field and magnetic field complex amplitudes depends on the proximity of the input beam polarisation to radial or azimuthal. As visible in the right part of Figure 20 showing the complex amplitude real part, the complex amplitude of electric and magnetic fields are in opposite phase when the spiral polarisation of the input beam is right handed. Figure 21 shows that they are in phase when the spiral polarisation of the input beam is left handed.

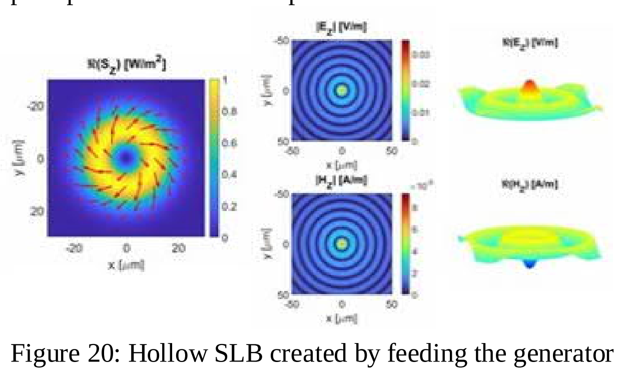

Figure 20: Hollow SLB created by feeding the generator with a beam having a right handed spiral polarization (between radial and azimuthal), see left part. The colour scale of the two plots at the centre represents the absolute value of the complex amplitude along z of the E field at top and magnetic field at bottom. On the right, the plots represent the real part of the complex amplitude along z for electric field, and for the magnetic field, at a given time, respectively at top and at bottom.

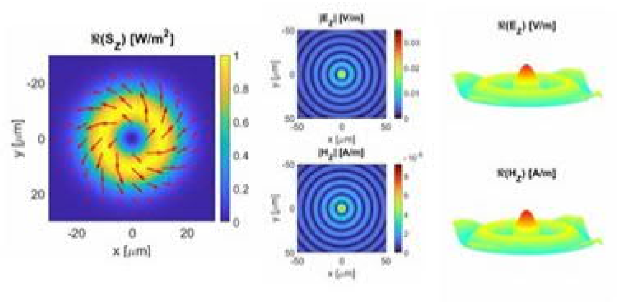

Figure 21: Hollow SLB created by feeding the generator with a beam having a left handed spiral polarization (between radial and azimuthal), see left part. The colour scale of the two plots at the centre represents the absolute value of the complex amplitude along z of the E field at top and magnetic field at bottom. On the right, the plots represent the real part of the complex amplitude along z for electric field, and for the magnetic field, at a given time, respectively at top and at bottom.

CONCLUSION

The on-going research related to the SLB reveals the numerous properties of this type of beams. However the results obtained up to now designate the SLB as a promising tool in the frame of development of long range optical alignment systems or large scale metrology. For example, its long range propagation capabilities and the low divergence of the central core allow a detection on a simple imaging sensor without using any imaging optics or projection screen and in a range of distances covering hundreds of meters without changing any of the parameters of the generator.

The theoretical study and the sophisticated simulation software tools developed in this frame allow to go further in the SLB knowledge. They permit for example the understanding of the effects of the symmetry breaking on beam straightness and the optimisation of the aperture to mitigate this effect.

In addition, it was demonstrated that Hollow Structured Laser Beams can be created using non-classical polarization for the beam illuminating the generator. These HSLBs present potential advantages for an alignment system. In particular, the beam core is dark and the range of the intensity between the darkest circles and the brightest zone is less than for a standard SLB. This facilitates, for example, the adjustment of the system to keep the signal within the dynamic range of an imaging detector such as a CMOS chip.

Some other research topics are under investigation such as the interferometry using SLB.

Moreover, the SLB presents many other properties, not developed in this paper, and which could be of interest in different professional domains.

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