

Characterization of the constituent wave of a diffracting and a nondiffracting axisymmetric laser beam

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Abstract: We show experimentally how diffracting and nondiffracting laser beams can be characterized through their one-dimensional constituent wave. Such a wave stems from an angular decomposition applicable to any cylindrically symmetric laser beam. In our experiment, spatial filtering in a 4-f system is used to generate the constituent wave of each beam under study. Standard one-dimensional root-mean-square (rms) parameters, such as the propagation factor and the generalized Rayleigh range, are then applied to determine the regime of propagation of the beams to characterize.

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1. Introduction

Numerous analytical solutions describing laser beams with cylindrical symmetry can be found in the literature. Laguerre-Gauss beams [1] present, for a given waist radius, a far-field divergence that is a function of their azimuthal and radial orders. Bessel beams [2] are known to exhibit a nondiffracting behavior but would require an infinite amount of energy for their realization. Other solutions, such as Bessel-Gauss beams [3,4], can propagate in either a diffracting or a nondiffracting regime, depending on the relative value of their parameters.

Recently, a scalar and paraxial analysis [5] has established more specific criteria to determine in a quantitative manner the regime of propagation of cylindrically symmetric laser beams. The approach relies on the fact that any laser beam of well-defined azimuthal order, hereafter called the resulting beam, can be constructed from a single wave, which has been

termed the constituent wave [5]. Such a wave diffracts along only one of its transverse axes (say the axis x) and propagates with an angle Θ from the propagation axis z of the resulting beam. In the spatial-frequency domain, the complex-amplitude profile $\tilde{U}_c(s_x, z)$ of the constituent wave is defined by [5]

$$\tilde{U}_c(s_x, z) \equiv H(s_x) s_x \tilde{U}(s_r = s_x, z), \quad (1)$$

where $H(s_x)$ is the unit-step function and $\tilde{U}(s_r, z)$ is the radial complex-amplitude profile of the resulting beam. The radial and the Cartesian spatial frequencies (in mm^{-1}) are respectively denoted s_r and s_x .

The one-dimensional character of a constituent wave allows its characterization in terms of root-mean-square (rms) parameters such as the M^2 factor and the generalized Rayleigh range z_R [6,7]. When applied to a constituent wave, these parameters will be respectively denoted as $M_c^2 = 4\pi\sigma_{x0}\sigma_{s_x}$ and $z_{R,c} = 4\pi\sigma_{x0}^2(M_c^2\lambda)^{-1}$ where σ_{x0} is the minimum rms width in the spatial domain, σ_{s_x} is the rms width in the spatial-frequency domain, and λ is the wavelength. The constituent wave defined by Eq. (1) leads naturally to a redefinition [5] of the geometrical depth of field $Z_{\max}$ (first introduced by Durnin *et al.* [2]) in terms of rms parameters,

$$Z_{\max} \equiv \frac{2\sigma_{x0}}{\tan \Theta} \equiv \frac{2\sigma_{x0}}{\lambda \bar{s}_x}, \quad (2)$$

where the second equality can be considered exact in the paraxial approximation. In this approximation, $\Theta = \lambda \bar{s}_x$, $\bar{s}_x$ being the first-order moment of the normalized intensity distribution in the spatial-frequency domain. This definition of $Z_{\max}$ is no more restricted to nondiffracting beams and the zone within $z = \pm Z_{\max}$ is called the geometrical interference zone. The regime of propagation – diffracting or nondiffracting – within this zone is then determined quantitatively by the following dimensionless ratio [5],

$$Q \equiv \frac{z_{R,c}}{Z_{\max}} \equiv \frac{\bar{s}_x}{2\sigma_{s_x}}, \quad (3)$$

called the quality factor (not to be confused with the propagation factor M^2). In general, a value of Q superior to a few units (typically 4) indicates that the resulting beam propagates in a nondiffracting regime within its geometrical interference zone [5].

In this paper, the constituent wave of a diffracting beam and that of a nondiffracting beam are experimentally observed and characterized in terms of their rms parameters. Experimental measurements were carried out on two axisymmetric laser beams produced by spatially filtering an Airy diffraction pattern. The first one is a diffracting beam that is nearly diffraction limited. The second one is a low quality nondiffracting beam (Q factor slightly superior to 4). The purpose of this comparison is to demonstrate the relevance of an approach based on the constituent wave to determine in a quantitative manner the regime of propagation of a cylindrically symmetric laser beam by using the quality factor Q . Such an approach gives an interesting picture to explain the physical origin of the nondiffracting character of a Bessel-type laser beam within its geometrical interference zone.

The paper is divided as follows. Section 2 describes the technique we have implemented to produce a diffracting and a nondiffracting beam by spatially filtering an Airy diffraction pattern. In section 3, we start from the analytical expression of the Airy radial amplitude profile to numerically model both beams under study. Invariant rms parameters relevant to the subsequent analysis are obtained from these simulations. In section 4, we describe the setup and the experimental procedure from which the resulting beams and their constituent waves were produced and characterized. In section 5, the results of the beam propagation experiment are presented in parallel for both the diffracting and the non-diffracting beams. Section 6 is devoted to a quantitative determination of the rms parameters of the constituent waves observed experimentally and to a comparison with parameters obtained from numerical simulations. Summary and final comments are grouped in section 7.

2. Production of diffracting and nondiffracting beams from an Airy diffraction pattern

In order to apply the representation based on constituent waves, an experiment was designed and conducted to produce both a diffracting beam and a Bessel-type nondiffracting beam. To ensure the generality of the experimental results, the comparison was made between a diffracting beam near the diffraction limit and a low quality (low value of Q) Bessel-type nondiffracting beam.

In the approach considered here, the experimental procedure must give an access not only to the resulting beam but also to its constituent wave. Since the constituent wave is defined in the spatial-frequency domain [see Eq. (1)], a direct access to this domain was preferable. Consequently, the experiment was based on a 4- f system like the one depicted in Fig. 1.

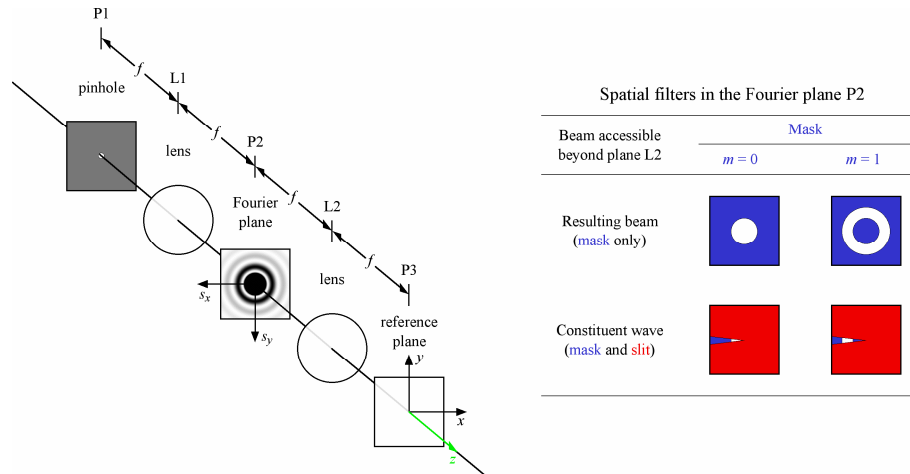


Fig. 1. Schematic diagram of the 4- f system used to produce the resulting beam (without the slit) and the constituent wave (with the slit) of a diffracting beam (with mask $m = 0$) and a Bessel-type nondiffracting beam (with mask $m = 1$). The four spatial filters used in the Fourier plane P2 are shown on the right-hand side of the 4- f system.

The first part of the 4- f system is used to produce the far-field intensity distribution of a small circular aperture (pinhole) located in plane P1. The Airy diffraction pattern obtained in plane P2 has a circular central lobe, denoted by $m = 0$, that is surrounded by concentric rings, denoted by $m = 1, 2, \dots$. The central lobe can be viewed, in a first approximation, as a two-dimensional Gaussian intensity distribution. The first ring, $m = 1$, exhibits the annular intensity distribution typically observed in the far field of a Bessel-type beam. Each of these lobes can be selected by introducing an appropriate amplitude mask in the Fourier plane P2. Both masks are shown on the right-hand side of Fig. 1. The mask $m = 0$ is opaque (blue area) over its entire surface except on its central circular area limited by the first zero of the Airy diffraction pattern. The mask $m = 1$ is opaque (blue areas) over its entire surface except on an annular area limited by the first and the second zeroes of the Airy diffraction pattern. The coincidence between the limits of each mask and the zeroes of the radial intensity distribution of the Airy diffraction pattern ensures a self-apodization of the secondary source produced by the insertion of each mask in the Fourier plane P2. This almost eliminates the effects of diffraction by hard edges. Such an apodization is advantageous for a characterization based on rms parameters. Indeed, it has been pointed out that diffraction by hard-edge apertures may lead to the divergence of rms parameters [8,9].

The transmission through each mask creates a secondary source in Fourier plane P2. Each secondary source acts as the far-field of the resulting beam produced by the 4- f system. The waist radius of the resulting beam associated with each mask is located in reference plane P3 which defines the origin $z = 0$ of the axis of propagation z (green axis in Fig. 1).

By superimposing an appropriate angular slit (shown in Fig. 1) over the mask, the radial complex-amplitude profile, in the spatial-frequency domain, is selected along the positive part of the axis s_x . The angular opening of the slit ensures the multiplication by s_x of the complex-amplitude profile hereby selected. Consequently, such a slit isolates a constituent wave in conformity with the definition given by Eq. (1). The constituent wave is then accessible experimentally in any plane located beyond plane L2 ($z > -f$).

It is important to note that the angular opening of the slit (exaggerated in Fig. 1) must be sufficiently small to obtain a constituent wave which is essentially one-dimensional. This condition is easily verified by comparing the lateral extent of the constituent wave along both transverse axes, x and y , in the reference plane P3. If the lateral extent Δy along the axis y is sufficiently large when compared to the lateral extent Δx along the axis x , diffraction is then negligible along the axis y and the constituent wave can be considered as one-dimensional. Since the Rayleigh range is proportional to the square of the lateral extent, an aspect ratio $\Delta y/\Delta x$ larger than 10 is generally acceptable. This aspect ratio must be verified in the reference plane P3 where Δx and Δy both have their minimum values. One also has to verify that the diameter of the lens in plane L2 is sufficiently large to prevent undesirable diffraction effects due to the truncation of the constituent wave, by the edge of the lens, along the axis y . Finally, both lenses must have an f-number sufficiently large to minimize the effects of aberrations, especially if singlet lenses are used in planes L1 and L2. Generally, an f-number equal or superior to 15 ensures for a paraxial behavior free of aberrations.

3. Numerical simulations

One of the main interests of the method presented in the previous section stems from the fact that the far-field diffraction pattern of a uniformly illuminated circular aperture is the well-known Airy diffraction pattern [1]. The analytic expression of this diffraction pattern can be used to numerically model the beams produced by this method since the amplitude in Fourier plane P2 (immediately after the mask m) is directly related to the spatial-frequency spectrum of the beam in reference plane P3. More specifically, in the spatial-frequency domain, the complex amplitude of the resulting beam produced in plane P3 ($z = 0$) is given by

$$\tilde{U}(s_r, z = 0) = \begin{cases} \frac{J_1(2\pi R s_r)}{2\pi R s_r} & \text{for } s_r \in [s_{\min}, s_{\max}[\\ 0 & \text{for } s_r \notin [s_{\min}, s_{\max}[\end{cases}, \quad (4)$$

where J_1 is the first-order Bessel function of the first kind and R is the radius of the circular aperture (pinhole) in plane P1. For the mask $m = 0$, $s_{\min} = 0$ and $s_{\max} = 6.098 \text{ mm}^{-1}$ whereas $s_{\min} = 6.098 \text{ mm}^{-1}$ and $s_{\max} = 11.17 \text{ mm}^{-1}$ for the mask $m = 1$. These specific values are applicable for a pinhole radius $R = 100 \text{ }\mu\text{m}$.

The complex amplitude of the constituent wave (when the angular slit is inserted over mask m) is then obtained by introducing Eq. (4) in Eq. (1):

$$\tilde{U}_c(s_x, z = 0) = \begin{cases} H(s_x) s_x \frac{J_1(2\pi R s_x)}{2\pi R s_x} & \text{for } s_x \in [s_{\min}, s_{\max}[\\ 0 & \text{for } s_x \notin [s_{\min}, s_{\max}[\end{cases}. \quad (5)$$

Starting from this expression and using the one-dimensional beam propagation method, we obtained the results illustrated in Figs. 2(a) for $m = 0$ and 2(b) for $m = 1$. The continuous red curves represent the lateral extent limits of the constituent wave given by $\bar{x}(z) \pm 2\sigma_x(z)$ whereas the dashed red lines represent the lateral extent limits of its geometrical projection defined by $\bar{x}(z) \pm 2\sigma_{x0}$. The light grey background represents the geometrical interference zone limited by $z = \pm Z_{\max}$ whereas the dark grey background, representing the confocal region, is limited by $z = \pm z_{R,c}$.

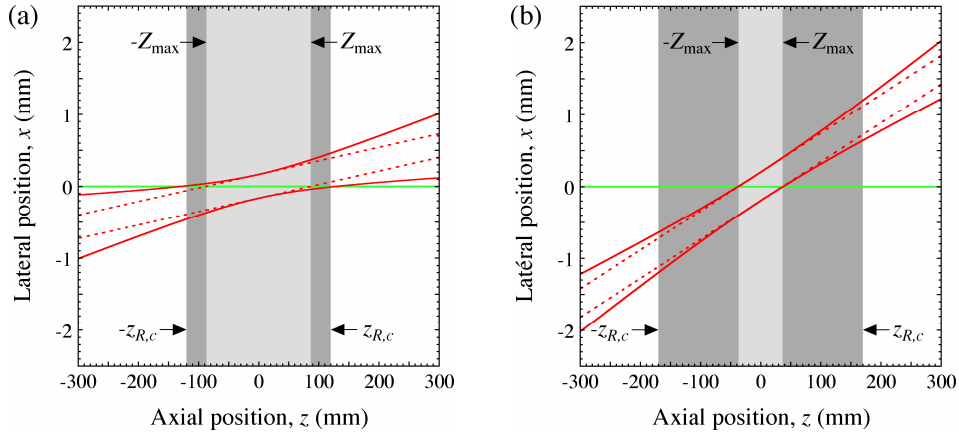


Fig. 2. Positions of the lateral extent limits of the constituent wave defined by $\bar{x}(z) \pm 2\sigma_x(z)$. The dashed curves, given by $\bar{x}(z) \pm 2\sigma_{x0}$, represent the limits of the geometrical projection. The axis of propagation of the resulting beam is shown in green. Colored backgrounds represent, respectively, the geometrical interference zone (light grey) and the confocal zone (dark grey). (a) Diffracting and (b) nondiffracting beams obtained, respectively, with the central lobe ($m = 0$) and the first annular lobe ($m = 1$) of the Airy diffraction pattern.

The most relevant rms parameters obtained from these simulations are listed in Table 1. Even though both constituent waves have comparable minimum rms widths σ_{x0} and propagation factors M_c^2 , they propagate at rather different angles Θ . Consequently, their geometrical depths of field $Z_{\max}$ and their quality factors Q are significantly different. Most importantly, the factor Q of the beam obtained with mask $m = 1$ is superior to 4, a value that is sufficiently high to consider this beam as nondiffracting. This is not the case for the beam produced with mask $m = 0$.

Table 1. Calculated values of the rms parameters of the constituent waves.

Symbol	Θ	σ_{x0}	$Z_{R,c}$	$Z_{\max}$	Q	M_c^2
Units	mrad	μm	mm	mm	-	-
$m = 0$	1.878	82.19	119.1	87.49	1.361	1.125
$m = 1$	5.402	99.00	170.4	36.65	4.649	1.142

4. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 3. The 632.8-nm linearly-polarized laser beam of a He-Ne laser (JDS-Uniphase, model 1135-P, ~18mW) was prepared with a 1.5-m focal length lens in order to illuminate the 100- μm radius electroformed pinhole located in plane P1 with a flat-wavefront Gaussian beam. The waist radius parameter w_0 in plane P1 was chosen to be sufficiently larger than the pinhole radius R in order to obtain an almost uniform illumination. In our experiment, $w_0/R \cong 9$. A corner cube retroreflector was used to center the beam impinging on the pinhole without changing its angular orientation. This procedure was critical in obtaining an Airy diffraction pattern with an azimuthally symmetric distribution of energy while keeping the alignment of the optical components following the pinhole. The 1-m focal length lens in plane L1 was a plano-convex lens with a 50-mm clear aperture. The mask ($m = 0$ or $m = 1$) was located a few millimeters before plane P2 and precisely centered on the axis of the 4-f system. Two razor blades were positioned in plane P2 to form a suitable angular slit ($\sim 2^\circ$ for $m = 0$ and $\sim 1^\circ$ for $m = 1$) with its summit precisely centered on the axis of symmetry of the 4-f system. Both blades were fixed on a translation stage (not shown) to allow for a precise insertion or removal of the slit into the 4-f

system. The 1-m focal length lens located in plane L2 was plano-convex with a 25-mm clear aperture. The CCD camera (DataRay, model WinCamD: 1200 x 1024 pixels, 4.65 x 4.65 μm^2 , 14-bit ADC) was located after an optical delay line allowing a sweep along the axis z slightly superior to 300 mm on either side of the reference plane P3. This plane was approximately located on the CCD camera when the optical delay line was in the middle of its total course (as shown in Fig. 3).

After introducing mask m , the corresponding resulting beam was observable with the CCD camera. Because of its symmetry, the resulting beam was used to locate the position of the axis of propagation z in the transverse plane. Then, by introducing the angular slit, the transverse intensity distribution of the constituent wave was measured by the CCD camera. Consequently, for any value of the optical delay, it was possible to characterize, both, the resulting beam and its constituent wave. All images were captured with an average over 20 successive frames. The variable attenuator and the integration time of the CCD camera were adjusted to obtain a saturation intensity slightly superior the maximum intensity in the acquisition plane. The dark signal was captured in the same conditions and subtracted from each image. A dynamic range of approximately 30 dB was achieved using this procedure.

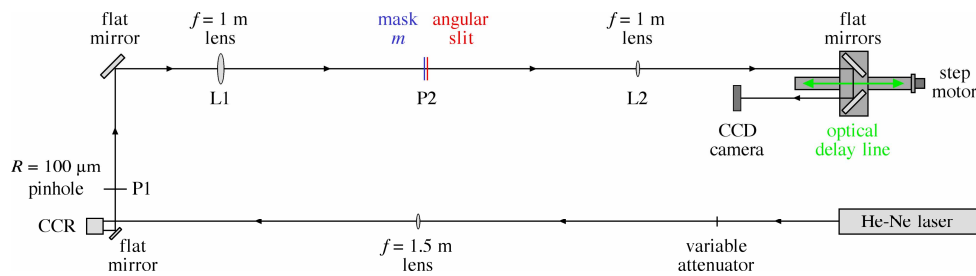


Fig. 3. Schematic diagram of the experimental setup. CCR stands for corner cube retroreflector.

5. Results of the beam propagation experiment

In the beam propagation experiment, the intensity distribution of the resulting beam and that of its constituent wave were captured in the reference plane $z = 0$ and in six planes on either side of the reference plane. The results obtained in seven of these thirteen planes are shown in Fig. 4. In Fig. 4(a), the resulting beam obtained with the mask $m = 0$ is almost Gaussian and exhibits a clear divergence on either side of its waist plane ($z = 0$). The corresponding images of its constituent wave exhibit the typical behavior expected from the constituent wave of a diffracting beam [5]. First, the divergence of the constituent wave is observable over an axial distance similar to that of the resulting beam. Secondly, the spatial broadening of the constituent wave is comparable to its lateral drift away from the propagation axis of the resulting beam. Consequently, there is always an overlap between the constituent wave and the axis of propagation. In Fig. 4(b), the resulting beam obtained with the mask $m = 1$ exhibits a clear conical structure and its distribution of intensity becomes rapidly annular. For such a beam, however, the constituent wave propagates at an angle Θ with the propagation axis z that is superior to its own divergence. Consequently, the constituent wave crosses completely the axis z before the occurrence of any significant spatial broadening due to diffraction.

In a first step toward a quantitative analysis, the intensity profiles along the axis x were extracted from images taken in each of the thirteen planes considered in the experiment. Intensity profiles of the resulting beam (blue curves) and their respective constituent waves (red curves) are shown in Fig. 5. Each profile is normalized to its absolute maximum. In Fig. 5(a), the diffracting beam obtained with the central lobe ($m = 0$) of the Airy diffraction pattern is considered. The resulting beam exhibits an almost Gaussian profile. Its constituent wave propagates with an angle Θ comparable to its half-divergence angle. Consequently, the constituent wave never escapes completely from the axis of propagation (green line) and there

is always a non negligible overlap between the lateral profile of the constituent wave and the axis z . In Fig. 5(b), the nondiffracting beam obtained with the first annular lobe ($m = 1$) of the Airy diffraction pattern is considered. The resulting beam exhibits the conical geometry of Bessel-type nondiffracting beams. Interference fringes are observable only near the reference plane $z = 0$ and the on-axis intensity rapidly becomes negligible away from this plane. The lateral intensity profile of its constituent wave completely crosses the axis of propagation of the resulting beam. In this case, the half-divergence angle of the constituent wave is much smaller than the absolute angle Θ between its direction of propagation and the axis of propagation of the resulting beam. The spatial broadening of the constituent wave is barely noticeable, even in planes $z = \pm 100$ mm. Clearly, the divergence of the resulting beam cannot be attributed, in this case, to the diffraction of the constituent wave.

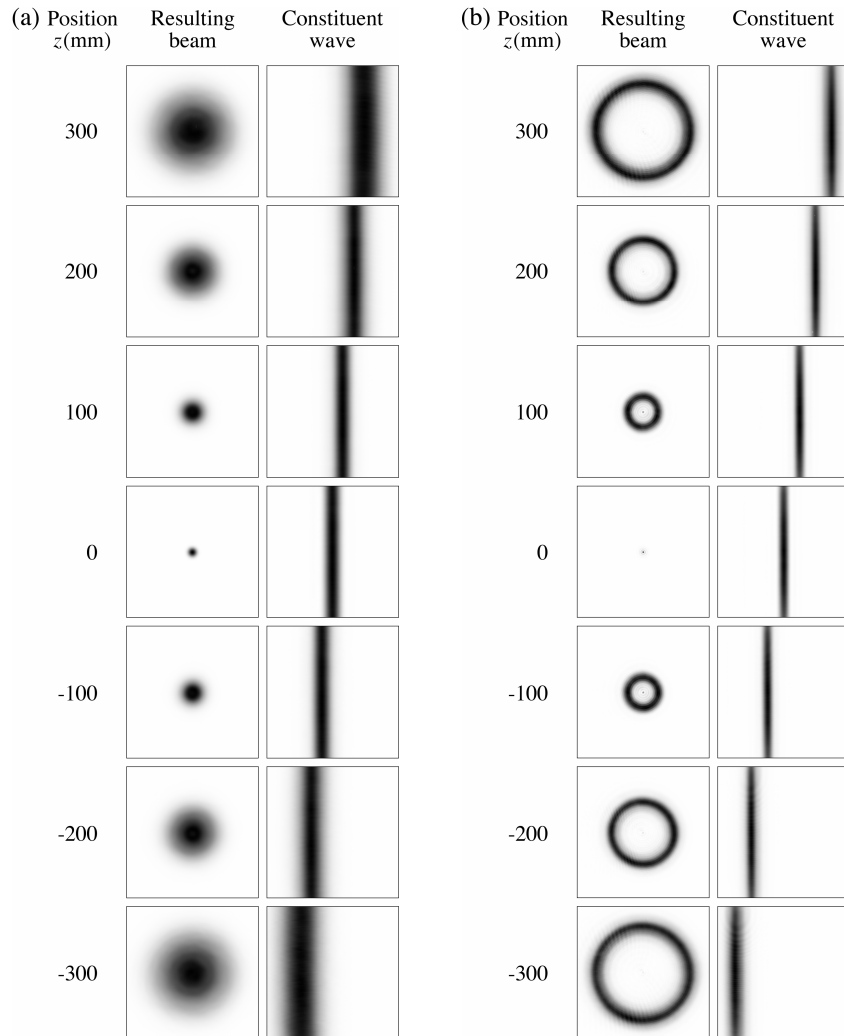


Fig. 4. Measured transverse intensity distributions of the resulting beam and the corresponding constituent wave along the axis of propagation z . (a) Diffracting and (b) nondiffracting beams obtained, respectively, with the central lobe ($m = 0$) and the first annular lobe ($m = 1$) of the Airy diffraction pattern. The axis of propagation z is located at the geometric center of each image. Images in (a) and (b) contain, respectively, 480×480 pixels ($2.23 \text{ mm} \times 2.23 \text{ mm}$) and 960×960 pixels ($4.46 \text{ mm} \times 4.46 \text{ mm}$).

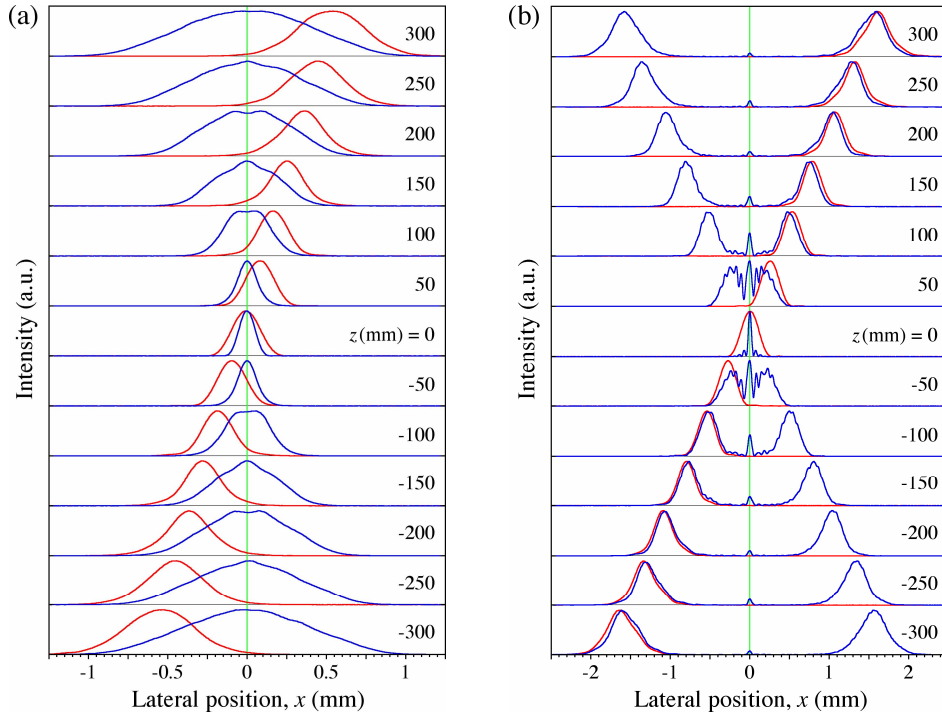


Fig. 5. Intensity profiles of the resulting beam (blue curves) and the constituent wave (red curves) along the axis x ($y = 0$) at thirteen axial positions. In each case, the green line represents the position of the propagation axis z of the resulting beam. Experimental results are shown for (a) the diffracting and (b) the nondiffracting beams obtained, respectively, with the central lobe ($m = 0$) and the first annular lobe ($m = 1$) of the Airy diffraction pattern.

6. Root-mean-square analysis of the constituent wave

The measured intensity profiles of each constituent wave (red curves in Fig. 5) were analyzed quantitatively in a two-step process. First, the lateral position $\bar{x}$ of the centroid was extracted in each transverse plane z . These positions are shown (red dots) in Figs. 6(a) and 6(b), respectively, for the constituent waves of the diffracting and nondiffracting beams. As expected from paraxial diffraction theory, the centroid of each constituent wave propagates along a straight line which can be interpreted as the direction of their respective wave vector [1]. Consequently, for each constituent wave, a least-square curve fit was made with the following linear equation,

$$\bar{x}(z) = \Theta(z - \delta z_l), \quad (6)$$

in order to determine the angle Θ between the direction of propagation and the axis of propagation z of the resulting beam (green lines in Fig. 6). The offset δz_l is there to take into account any error in the localization of the reference plane made prior to the series of measurements. The results of both linear curve fits (red dashed lines) and those obtained from numerical simulations (black lines) are also shown in Fig. 6.

Secondly, the rms width σ_x of the constituent wave was extracted in each transverse plane z . These rms widths are shown (red dots) in Fig. 7 for each constituent wave. In this case, a weighted least-square curve fit was made with the hyperbolic law of propagation [6,7],

$$\sigma_x(z) = \sigma_{x0} \left[1 + \left(\frac{z - \delta z_h}{z_{R,c}} \right)^2 \right]^{1/2}, \quad (7)$$

in order to determine the minimum rms width σ_{x0} and the generalized Rayleigh range $z_{R,c}$. Again, an offset δz_h is there to take into account any error in the localization of the reference plane. The weight attributed to each experimental value of σ_x was proportional to σ_x^{-2} for reasons explained in details by Johnston, Jr. [10]. The results of both curve fits (red dashed lines) and those obtained from numerical simulations (black lines) are also shown in Fig. 7.

Parameters extracted from the curve fits described above are listed in Table 2 with values of rms parameters ($Z_{\max}$, Q , and M_c^2) deduced from the same curve fits. Values obtained from numerical simulations are printed in Table 2 over a grey background.

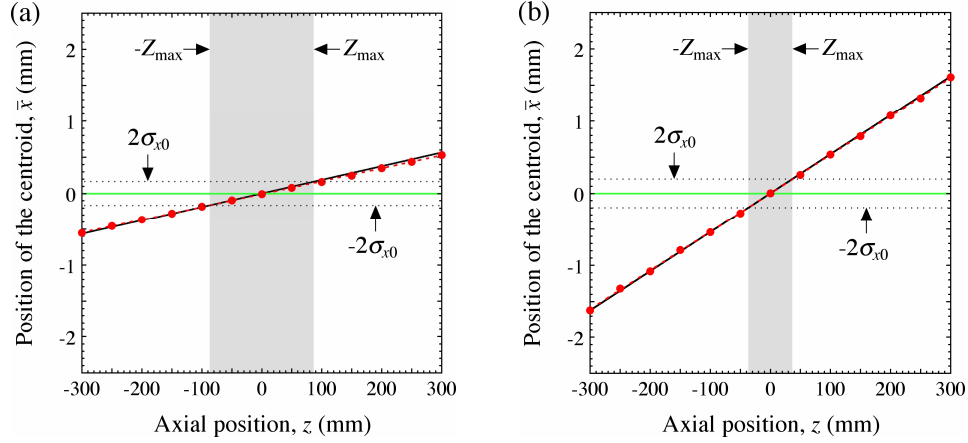


Fig. 6. Measured lateral positions of the centroid (red dots) of the constituent wave as a function of the axial position z . The black line is obtained from numerical simulations and the red dashed line is the result of the linear curve fit based on experimental data. The light grey background represents the geometrical interference zone. (a) Diffracting and (b) nondiffracting beams obtained, respectively, with the central lobe ($m = 0$) and the first annular lobe ($m = 1$) of the Airy diffraction pattern.

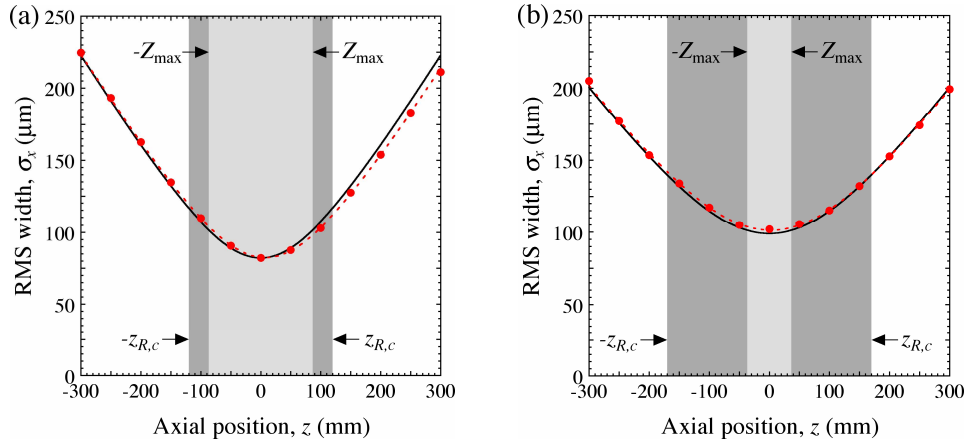


Fig. 7. Measured rms widths (red dots) of the constituent wave as a function of the axial position z . The black curve is obtained from numerical simulations and the red dashed curve is the result of the hyperbolic curve fit based on experimental data. Colored backgrounds represent, respectively, the geometrical interference zone (light grey) and the confocal zone (dark grey). (a) Diffracting and (b) nondiffracting beams obtained, respectively, with the central lobe ($m = 0$) and the first annular lobe ($m = 1$) of the Airy diffraction pattern.

Table 2. Results of the linear and the hyperbolic curve fits. Results expected from numerical simulations (presented in Table 1) are printed over a grey background.

Symbol	Linear fits		Hyperbolic fits			Calculated parameters		
	Θ	δz_l	σ_{x0}	$z_{R,c}$	δz_h	$Z_{\max}$	Q	M_c^2
Units	mrad	mm	μm	mm	mm	mm	-	-
$m = 0$	1.878	0	82.19	119.1	0	87.49	1.361	1.125
$m = 0$	1.782	5.631	82.40	122.1	7.747	92.48	1.320	1.104
$m = 1$	5.402	0	99.00	170.4	0	36.65	4.649	1.142
$m = 1$	5.341	0.522	101.3	175.7	2.691	37.93	4.632	1.160

Apart from the slight offsets δz_l and δz_h , the experimental results listed in Table 2 are in very good agreement with values expected from the numerical simulations presented in Section 2. Most importantly, for the beam generated with mask $m = 1$, a value of Q superior to 4 confirms its nondiffracting character. Indeed, it can be seen in Fig. 7(b) that the rms width of the constituent wave of this beam is almost invariant within the geometrical interference zone. This is simply due to the fact that the geometrical interference zone (limited by $z = \pm Z_{\max}$) is shorter than the confocal zone of the constituent wave (limited by $z = \pm z_{R,c}$) by a factor equal to the value of Q [see Eq. (3)]. The relative axial extent of these zones, given by Q , is thus a critical parameter in determining the regime of propagation of a cylindrically symmetric laser beam.

7. Conclusion

In this paper, we have introduced an experimental technique allowing for the production of diffracting and Bessel-type nondiffracting laser beams from an Airy diffraction pattern. By spatially filtering the central lobe and the first annular ring, an almost Gaussian diffracting beam and an almost Bessel-Gauss nondiffracting beam were respectively produced. The use of a thin angular slit allowed us to produce the constituent wave of each beam under study. These constituent waves were characterized exhaustively along the axis of propagation and on either side of the reference plane corresponding to their waist. The evolution of the centroid lateral position and the rms width of the constituent waves were determined from these measurements. Very good agreement has been found with values expected from numerical simulations.

Even though the experiment was done with specific beams, its results show a first experimental validation of the approach using constituent waves to distinguish in quantitative terms the regime of propagation – diffracting or nondiffracting – of cylindrically symmetric laser beams. The experimental technique presented here could be generalized to laser beams with a nonzero azimuthal order.

The quality factor Q defined by the ratio of the generalized Rayleigh range $z_{R,c}$ of the constituent wave and the rms value of the geometrical depth of field $Z_{\max}$ allows the determination of the nondiffracting character of a laser beam with a single number.

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