Diffraction-free subwavelength-beam optics

S. V. Kukhlevsky, M. Mechler

Institute of Physics, University of Pecs, Ifjusag u. 6, Pecs 7624, Hungary

Abstract

Diffraction is a fundamental property of light propagation. Owing to this phenomenon, light diffracts out in all directions when it passes through a subwavelength slit. This imposes a fundamental limit on the transverse size of a light beam at a given distance from the aperture. We show that a subwavelength-sized beam propagating without diffractive broadening can be produced in free space by the constructive interference of multiple beams of a Fresnel source of the respective high-refraction-index waveguide. Moreover, it is shown that such a source can be constructed not only for continuous waves, but also for ultra-short (near single-cycle) pulses. The results theoretically demonstrate the feasibility of completely diffraction-free subwavelength-beam optics, for both continuous waves and ultra-short pulses. The approach extends operation of the near-field subwavelength-beam optics, such as near-field scanning optical microscopy and spectroscopy, to the ”not-too-distant” field regime (0.5 to about 10 wavelengths).

PACS numbers: 42.25.Fx - Diffraction and scattering. 42.65.Re - Ultrafast processes; optical pulse generation and pulse compression. 07.79.Fc - Near-field scanning optical microscopes.
I. INTRODUCTION

Diffraction is one of the fundamental laws of physics. It affects all classical and quantum mechanical fields without exception. Owing to the law, it is impossible in quantum mechanics to define at a given time both the position of a matter wave-packet and its direction to an arbitrary degree of accuracy. Because of the diffraction phenomenon, light spreads out in all directions after passing a slit smaller than its wavelength. The harder one tries to decrease the beam transverse dimension by narrowing the slit, the more it broadens out. Similarly, the beam width dramatically increases with increasing the distance from the slit. Thus, the diffraction imposes a fundamental limit on the transverse dimension of a beam at a given distance from an aperture and consequently limits the resolution capabilities and makes harder the position requirements of subwavelength-beam optical devices, such as near-field scanning optical microscopes (NSOM) and spectroscopes (see, for example [1, 2, 3, 4]).

In order to completely avoid the diffractive broadening of a beam, generally speaking, one can use the two main approaches. A light beam can be confined to subwavelength transverse dimensions by multiple total internal reflections at boundaries of a high-refractive-index waveguide [5]. Unfortunately, the guided beam spreads out in all directions after passing the waveguide output-aperture. Another approach uses "diffraction-free" beams [6, 7, 8, 9]. A diffraction-less beam, for instance a Bessel-type beam, propagates in free space without diffractive broadening. Although, the diffraction-free beams, the widths of which greatly exceed the wavelength, have been well understood and realized experimentally, neither theoretical principle nor blueprint of the diffraction-free subwavelength-beam optics has been presented up to now.

In the present article we show that a subwavelength-sized beam propagating without diffractive broadening can be produced in free space by the constructive interference of multiple beams of a Fresnel source of the respective high-refraction-index waveguide. The results theoretically demonstrate the feasibility of completely diffraction-free subwavelength-beam optics, for both continuous waves and ultra-short pulses. The approach extends operation of the near-field subwavelength-beam optics to the "not-too-distant" field regime (0.5 to about 10 wavelengths).
II. THEORETICAL ANALYSIS AND DISCUSSION

In this section, we show that the diffractive broadening of a subwavelength-sized beam can be completely avoided. The approach involves a recently established relation between the waveguide and free-space optics \[10, 11\]. Although, these areas of optics are usually considered to be independent of each other, it was showed that the fields confined by a high-refractive-index waveguide, whose width exceeds the wavelength \(\lambda\), could be reproduced in free space by a Fresnel source of this waveguide. The basic concept of the Fresnel-waveguide source of a diffraction-free beam is quite simple. The concept is demonstrated in Fig. 1 for a plane-parallel guide having total-reflection walls. In the approach, the boundaries of the waveguide are replaced by virtual sources \[10\]. The diffraction-free beam \(E'(x', z, t)\) confined by the waveguide is supported in free space at points \((x', z)\) by the constructive interference of multiple beams \(E_n'(x', z, t)\) of a Fresnel source of the waveguide:

\[
E'(x', z, t) = \sum_{n=-M}^{M} E_n'(x', z, t),
\]

(1)

where the number \(2M + 1\) of the beams \(E_n'(x', z, t)\) depends on their widths at the distance \(z\) from the source; \(n = 0, \pm 1, \pm 2, \ldots, \pm M\); \(z > 0\) and \(|x'| < a\). The beam \(E_n'(x', z, t)\) is emerged from the \(n\)-th zone of the Fresnel source having the field distribution

\[
E_n(x, 0, t) = E_0(x_n, 0, t)\exp(i\pi n),
\]

(2)

which is obtained by the periodic \((x_n = x \pm 2na)\) translation of the field \(E_0(x, 0, t)\) and the \(\pi n\)-change of its phase; \(E_0(x, 0, t)\) is the field at the input aperture; \(z = 0\) and \(|x| < a\). Thus, the Fresnel-waveguide \(\sum_{n=-M}^{M} E_n'(x', z, t)\) is constructed by the periodic translation and the phase change of the beam \(E_0'(x', z, t)\) emerged from the waveguide aperture.

The above-described approach, which was originally developed by using the Helmholtz-Kirchhoff integral theorem \[10\], fails when the waveguide width \(2a\) is close to the wavelength \(\lambda\). It is surprising that in the general form of Eqs. 1 and 2, as it will be shown below, the approach provides solution of the problem also in the case of subwavelength waveguides (see, Figs. 2-4). Figure 2 presents the normalized energy flux distribution \(S_{\text{norm}}^z = (c/8\pi)\text{Re}(\bar{E} \times \bar{H}^*)_z\) of a diffraction-less beam computed for the Fresnel source of a subwavelength \((a = 0.05\lambda)\) waveguide, at the three distances \(z\) from the source. In the figure the normalized flux of a single beam, which was used in the construction of the Fresnel
source, is shown at \( z = 6a \) for comparison. The Fresnel waveguide \( E'(x', z, t) \) was constructed by the translation of the single beam \( E_0'(x', z, t) \) and the periodical change of its phase (see, Eqs. 1, 2 and Fig. 1). The single beam \( E_0'(x', z, t) \) is formatted by transmission of a plane monochromatic wave through a subwavelength waveguide (thick slit) with perfectly conducting walls. The details of the computations of the electric \( \vec{E} = (E_x, 0, E_z) \) and magnetic \( \vec{H} = (0, H_y, 0) \) field distributions of the transmitted beam are presented in Refs. [12, 13]. The full width at half maximum (FWHM) and the energy flux of the diffraction-less subwavelength beam versus the distance \( z \) from the Fresnel-waveguide source are shown in Fig. 3, in comparison to that of the single beam produced by the slit. The results presented in Figs. 2 and 3 demonstrate theoretically the feasibility of completely diffraction-free subwavelength-beam optics. Notice, that at the distance \( z = a \), which is generally accepted for practical near-field scanning optical microscopy [12], FWHM of the diffraction-free beam is about two times lower than that of the single beam. This should provide two-times increase of the spatial resolution of the near-field scanning optical microscopy and spectroscopy. Although, the Fresnel-waveguide source producing a subwavelength diffraction-free continuous wave is already an unexpected finding, an example presented in Fig. 4 demonstrates that such a source can be constructed also for the ultra-short (near single-cycle) pulses. The figure shows the computed electric field \( E_x \) of the diffraction-free subwavelength pulse formatted by the Fresnel-waveguide source at the distance \( z = 3a \). The pulse used for the construction of the Fresnel waveguide is formatted by transmission of the femtosecond (near single-cycle) pulse through the slit [13]. It should be noted that the diffraction-free pulse (Fig. 4) is not in conflict with the recently established uncertainty relation between spatial and temporal uncertainties of a wave-packet [14] because of the multiple-beam nature of the Fresnel-waveguide source. The diffraction-free pulse is localized in space and time at the expense of increasing the number of beams (pulses) that support the diffraction-free wave-packet under its free-space propagation.

The results theoretically demonstrate the feasibility of completely diffraction-free subwavelength-beam optics, for both continuous waves and ultra-short pulses. The approach extends operation of the near-field subwavelength-beam optics to the far-field regime \( (z > 0.5\lambda) \). Notice, in this connection, that the number of the Fresnel beams supporting the diffraction-free beam increases and the beam intensity decreases with increasing the distance \( z \) (see, Figs. 1-3). Therefore, the effective operation of the optics is restricted to
the "not-too-distant" field region (0.5 to about 10 wavelengths). The optics could improve spatial and temporal resolution capabilities and positioning requirements of the near-field scanning optical microscopy and spectroscopy. The approach could also be used for many other subwavelength-photonic purposes, such as sensors, communications, optical switching devices and microsources. It should be noted that the method can be extended to the 3-dimensional beams. In this case, one could use the Fresnel sources of 3-dimensional subwavelength waveguides [15]. The concept of the Fresnel sources of subwavelength waveguides helps us to understand the studies [16, 17], which have demonstrated that a series of parallel grooves surrounding a nanometre-sized slit in a metal film produces a micrometer-size beam that spreads to an angle of only few degrees. Another relevant result is achievement of about 20 percent reduction of far-field diffraction by structured apertures [18]. The evident parallelism between mechanisms of the formation of a subwavelength waveguide in free space by the Fresnel multiple-beam source and the enhancement of light transmission by subwavelength aperture arrays [19] should also be noted. The presented theoretical principle of the Fresnel-waveguide source of a diffraction-free subwavelength beam could be realized experimentally using the techniques [16, 17, 18], the air and dielectric guide bends or the hybrid hetero structures (for example, see the study [20] and references therein).

III. CONCLUSION

We have showed that a subwavelength-sized beam propagating without diffractive broadening can be produced in free space by the constructive interference of multiple beams of a Fresnel source of the respective high-refraction-index waveguide. The presented results theoretically demonstrate the feasibility of completely diffraction-free subwavelength-beam optics, for both continuous waves and ultra-short pulses. The approach extends operation of the near-field subwavelength-beam optics to the "not-too-distant" field regime (0.5 to about 10 wavelengths).

Acknowledgments

This study was supported by the Fifth Framework of the European Commission (Financial support from the EC for shared-cost RTD actions: research and technological develop-
ment projects, demonstration projects and combined projects. Contract NG6RD-CT-2001-00602). The authors thank the Computing Services Centre, Faculty of Science, University of Pecs, for providing computational resources.

[1] L. Rayleigh, Philos. Mag. XLIV, 28 (1897).
[2] H.A. Bethe, Phys. Rev. 66, 163 (1944).
[3] E.A. Ash, G. Nicholls, Nature 237, 510 (1972).
[4] E. Betzig, et al, Science 251, 1468 (1991).
[5] D. Marcuse, Theory of Dielectric Optical Waveguides (Academic Publishers, New York, 1974).
[6] J.N. Brittingham, Appl. Phys. 54, 1179 (1983).
[7] R.W. Ziolkowski, J. Math. Phys. 26, 861 (1985).
[8] J. Durnin, et al, Phys. Rev. Lett. 58, 1499 (1987).
[9] F. Gori, et al, Opt. Commun. 64, 491 (1987).
[10] S.V. Kukhlevsky, Europhys. Lett. 54, 461 (2001).
[11] J. Canning, Opt. Commun. 207, 35 (2002).
[12] E. Betzig, A. Harootunian, A. Lewis, M. Isaacson, Appl. Opt. 25, 1890 (1986).
[13] S.V. Kukhlevsky, M. Mechler, J. Opt. A: Pure Appl. Opt. 5, 256 (2003).
[14] S.V. Kukhlevsky, G. Nyitray, Opt. Commun. 209, 377 (2003).
[15] S.V. Kukhlevsky, G. Nyitray, J. Mod. Opt. 50, 2043 (2003).
[16] H.J. Lezec, et al, Science 297, 820 (2002).
[17] L. Martin-Moreno, et al, Phys. Rev. Lett. 90, 167401 (2003).
[18] A. Dogariu, et al, Opt. Commun. 220, 223 (2003).
[19] T.W. Ebbesen, et al., Nature 391, 667 (1998).
[20] A. Chutinan, S. John, O. Toader, Phys. Rev. Lett. 90, 123901 (2003).
FIG. 1: The construction of a Fresnel source for a plane-parallel waveguide having total-reflection walls.
FIG. 2: The normalized energy flux distribution $S_{z}^{\text{norm}}(x')$ of a diffraction-free subwavelength beam $E'(x', z, t)$ at different distances $z$ from the Fresnel source of the waveguide: A - $a$, B - $3a$, and C$_{\text{Multi}}$ - $6a$. A single beam $E'_0(x', z, t)$ used for construction of the source is produced by a 50-nm slit (waveguide) in a perfectly conducting screen of thickness $b = 50\text{nm}$. The normalized energy flux distribution C$^\text{Single}$ of this beam is shown at $z = 6a$ for comparison. The number $2M + 1$ of used beams for A and B is 51, for C$^\text{Multi}$ is 501; $a = 0.05\lambda$ and $\lambda = 500\text{nm}$.
FIG. 3: Full width at half maximum (FWHM) Multi and energy flux $S_z^{Multi}(x' = 0, z)$ of a diffraction-less subwavelength beam $E'(x', z, t)$ versus distance $z$ from the Fresnel source of the waveguide. The width and flux of a single beam $E_0'(x', z, t)$ used for construction of the source are shown for comparison. Here, the waveguide parameters are the same as indicated in Fig. 2. The number $2M + 1$ of used beams is 501; $a = 0.05\lambda$ and $\lambda = 500\text{nm}$. 
FIG. 4: The computed electric field $E_x$ of the diffraction-less femtosecond (near single-cycle) pulse $E'(x', z, t)$ produced by the Fresnel source of the subwavelength waveguide at the distance $z = 3a$. The parameters of the waveguide are the same as indicated in Fig. 2. A single pulse $E_0'(x', z, t)$ used for construction of the source has the pulse length $\tau = 2fs$ and central wavelength of the wave-packet $\lambda_0 = 500nm$. The number of beams (pulses) is $2M + 1 = 18$; $a = 0.05\lambda_0$. 