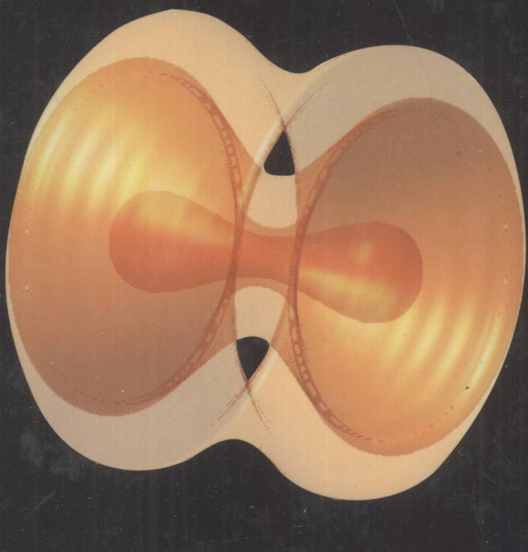
Localized Waves



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Preface

Diffraction and dispersion effects have been well known for centuries and are recognized to be limiting factors in many industrial and technology applications based, for example, on electromagnetic beams and pulses. Diffraction is an always-present phenomenon, affecting two- or three-dimensional waves traveling in nonguiding media. Arbitrary pulses and beams contain plane-wave components that propagate in different directions, causing a progressive increase in their spatial width along propagation. Dispersion is due to the dependence of the material media (refractive index) with frequency: therefore, each pulse's spectral component propagates with a different phase velocity, so that an electromagnetic pulse will suffer a progressive increase in its temporal width along propagation. It is clear that these two effects may be a serious restriction for applications where it is highly desirable that the beam keeps its transverse localization or the pulse keeps its transverse localization and/or temporal width along propagation, which might be desirable, for example, in free-space microwave, millimetric wave, terahertz and optical communications, microwave and optical images, optical lithography, and optical tweezers. As a consequence, the development of techniques capable of alleviating signal degradation effects caused by these two effects is of crucial importance.

Localized waves, also known as nondiffractive waves, arose initially as an attempt to obtain beams and pulses capable of resisting diffraction in free space for long distances. Such waves were obtained initially theoretically as solutions to the wave equation in the early 1940s (J. A. Stratton, *Electromagnetic Theory*, McGraw-Hill, New York, 1941), and were demonstrated experimentally in 1987 (J. Durnin, J. J. Miceli, and J. H. Eberly, Diffraction-free beams, *Phys. Rev. Lett.*, vol. 58, pp. 1499–1501, 1987). Nowadays localized waves constitute a growing and dynamic research topic, not only in relation to nondispersive free space (or vacuum), but also for dispersive, nonlinear, and lossy nonguiding media. Taking into account the significant amount of exciting and impressive results published especially in the last five years or so, we decided to edit a book on this topic, the first of its kind in the literature. The book is composed of 13 chapters authored by the most productive researchers in the field, with a well-balanced presentation of theory and experiment.

In Chapter 1, Recami et al. present a thorough review of localized waves, emphasizing the theoretical foundations along with historical aspects and the interconnections of this subject with other technology and scientific areas.

In Chapter 2, Zamboni-Rached et al. discuss in detail the theoretical structure of localized waves, and some applications are presented, among which frozen waves are of particular interest.

In Chapter 3, Besieris and Shaarawi present a hybrid spectral representation method which permits a smooth transition between two seemingly disparate classes of finite-energy spatiotemporally localized wave solutions to the three-dimensional scalar wave equation in free space: superluminal (X-shaped) and luminal (FWM-type) pulsed waves. An additional advantage of the hybrid form is that it obviates the presence of backward wave components, propagating at the luminal speed c, that have to be minimized in practical applications. A modified hybrid spectral representation method has also been presented which permits a seamless transition from superluminal localized waves to exact luminal splash modes. Within the framework of a certain parametrization, the latter are rendered indistinguishable from the paraxial luminal finite-energy-focused pulsed beam solutions.

In Chapter 4, Jian-yu Lu describes X-waves in depth, providing generalized methods for obtaining such waves through proper transformations, related primarily to the Lorentz transformation. X-wave solutions to Schrödinger and Klein–Gordon equations are also provided. In addition, the potential application of X-waves in medical ultrasound imaging is demonstrated experimentally.

In Chapter 5, Salo and Friberg show theoretically that diffraction-free wave propagation can also be achieved in anisotropic crystalline media. They explicitly analyze the effect of arbitrary anisotropies on both continuous-wave and pulsed nondiffracting fields. Due to beam steering and other effects, generation of nondiffracting waves in anisotropic media poses new challenges, and the authors propose an efficient scheme for the generation and detection of a continuous-wave beam in a crystal wafer.

In Chapter 6, Mugnai and Mochi explore Bessel X-waves' ability to provide localized energy and to exhibit superluminal propagation in both phase and group velocities (as verified experimentally). The authors also describe the ability of such waves to travel through a classically forbidden region (tunneling region) with no shift in the direction of propagation, which makes them different and unique with respect to ordinary waves.

In Chapter 7, Reivelt and Saari focus on the physical nature and experimental implementation or generation of localized waves. The authors demonstrate that the angular spectrum representation and the tilted pulse representation of localized waves are suitable tools for achieving these purposes. They explain the concepts and results of their experiments, where the realizability of Bessel X-waves and focus wave modes was verified for the first time.

In Chapter 8, Porras et al. present an interesting discussion of linear bullets, three-dimensional localized waves or particlelike waves propagating across a host medium, defeating diffraction spreading and dispersion broadening. Special attention is given to the generation of these bullets in practical settings by optical devices or by nonlinear means, showing the intimate relation between linear and nonlinear approaches to wave bullets, as in light filaments. The advantage of linear bullets with respect to standard wave packets (Gaussian-like) is also demonstrated for a variety of applications, such as laser writing in thick media, ultraprecise microhole drilling for photonic-crystal fabrication, and laser micromachining.

In Chapter 9, the theory of X-waves in nonlinear materials is discussed thoroughly by Conti and Trillo. Potential applications in light-matter interactions at high laser intensities in quantum optics and on the theoretical prediction of X-waves in Bose–Einstein condensates are pointed out.

In Chapter 10, by Kukhlevsky, the problem of spatial localization of light in free space on a nanometer scale is presented in detail. The author shows that a subwavelength nanometer-sized beam propagating without diffractive broadening can be produced by the interference of multiple beams of a Fresnel light source of the respective material waveguide. The results demonstrate theoretically the feasibility of diffraction-free subwavelength-beam optics on a nanometer scale for both continuous waves and ultrashort (near-single-cycle) pulses. The approach extends the operational principle of near-field subwavelength-beam optics, such as near-field scanning optical microscopy, to the "not-too-distant" field regime (up to about 0.5 wavelength). The chapter includes theoretical illustrations to facilitate an understanding of the natural spatiotemporal broadening of light waves and the physical mechanisms that contribute to the diffraction-free propagation of subwavelength beams in free space.

In Chapter 11, Grunwald et al. show experimentally that ultraflat thin-film axicons enable the real physical approximation of nondiffracting beams and X-pulses of extremely narrow angular spectra. By self-apodized truncation of Bessel–Gauss pulses (coincidence of first field minimum with the rim of an aperture), needle-shaped propagation zones of large axial extension can be obtained without additional diffraction effects. The signature of undistorted progressive waves was indicated for such needle beams by the fringe-free propagation characteristics and ultrabroadband spatio-spectral transfer functions.

In Chapter 12, Longhi and Janner provide a general overview of wave localization (in a weak sense) for an important and novel class of inhomogeneous periodic dielectric media (i.e., in photonic crystals), which have received increasing attention in recent years. Compared to wave localization in homogeneous media, such as in a vacuum, the presence of a periodic dielectric permittivity strongly modifies the space–time dispersion surfaces and hence the types of localized waves that may be observed in photonic crystals.

In Chapter 13, Bouchal et al. focus on theoretical and experimental problems of nondiffracting and singular optics. Particular attention is devoted to physical properties, methods of experimental realization, and potential applications of single and composed vortex fields carried by a pseudo-nondiffracting background beam. The unique propagation effects of vortex fields are pointed out, and consequences of their spiral phase singularities manifested by a transfer of the orbital angular momentum are also discussed. The complex vortex structures whose parameters and properties are controlled dynamically by a spatial light modulation provide advanced methods of encoding and recording of information and can be utilized effectively in optical manipulations. Spatially localized vortex structures can be extended into nonstationary optical fields where novel spatiotemporal effects and applications can be expected.

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The Editors

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