Conclusion

In the book, attention is paid to the diffraction of laser radiation on nanoscale inhomogeneities and optical nanostructures and also focusing of light in nanosized spaces. The authors applied their experience in the field of computer diffractive optics to solving nanophotonics problems. Based on mathematical modelling and numerical solution of inverse problems of the theory of diffraction of light, new devices containing diffractive optical elements (DOE), significantly extending the component base of nanophotonics, were investigated and constructed. The study of the diffraction of light is based on the solution Maxwell's equations in different ways: the difference method (FDTD-method), the beam propagation method (BPM-method), the method of coupled waves (RWCA), integral methods for solving diffraction problems, the method of finite and boundary elements, the method of matched sinusoidal modes. These and other methods are used in the book for the simulation of light diffraction on sub-wavelength gratings profiled metal–dielectric heterostructures, metallic nanorods, two-dimensional and three-dimensional photonic crystals, photonic–crystal fibres and lenses and on other nanophotonics devices. The optical manipulation of micro- and nano-objects with singular vortex laser beams is studied and the problem of sharp sub-wavelength focusing of laser light having radial polarization is also solved.

According to the authors, the following are actual directions of the development of diffractive nanophotonics.

• Research of extraordinary (resonance) of the optical and magneto-optical effects formed in diffraction of electromagnetic waves on heterostructures containing a regular system of curvilinear steps or gaps. The most interesting are radially symmetric heterostructures containing dielectric and metal layers, perforated by a concentric system of annular slits. There is sufficient evidence to suggest the presence in radially symmetric heterostructures of a whole spectrum of resonance effects that exist in two-dimensional structures and including extraordinary transmission, magneto-optical effects associated with resonance changes in the spectra of passage and reflection and rotation of the polarization plane due to the change of magnetization, formation of areas with a high degree of localization of energy due to the interference of fading and plasmon waves. The presence of the central zone allows one to expect new optical effects related with increased energy and localization of the light wave energy in the centre of the structure, as well as with focusing in the centre of the structure of plasmon and quasi-plasmon modes.

• An important element in the study of diffractive structures with curved areas is the creation of efficient computational methods of electromagnetic simulation. In this case, it is advisable to solve Maxwell's equations using selected curvilinear coordinates. In particular, the radially symmetric structures have cylindrical symmetry. For efficient simulation of diffraction in such structures it is necessary to develop a modal method for solving diffraction in cylindrical coordinates. In this method, the incident and scattered electromagnetic field and also the field within the layers of the structure will be presented in the basis of conical waves.

• In the field of plasmonics it is interesting to study metal–dielectric heterostructures with magnetized layers in problems of the control of surface electromagnetic waves (SEW) and the formation of SEW interference patterns. In such heterostructures we can expect new magneto-optical effects associated with the change of the form of the interference pattern of SEW depending on the magnetization of the layers. When SEW passes through a magnetized diffraction structure just above the surface of SEW propagation, the change of magnetization can provide new opportunities for the modulation of SEW parameters. Thus, the prospects of this research are related with better control of SEW due to changes in the magnetization of the heterostructure layers. An important area of research is also the study of plasmonic effects in the radial heterostructures. In particular, it is of great interest to study heterostructures consisting of a radial diffractive grating and a uniform metal layer. Such structures can shows the formation of ring interference patterns of surface plasmons and their focusing in the centre of the structure on the surface of the metallic layer.

• Of great interest is the further study of gradient photonic crystals, including photonic–crystal lenses to create nanophotonic devices that allow selective focusing of laser light with a certain wavelength and overcoming the diffraction limit. The main difficulty in modelling gradient photonic crystals is that they have impaired spatial periodicity and, therefore, no complete band gaps. However, the properties of frequency selectivity are retained because their thickness is much greater than the light wavelength. The gradient photonic crystals have a frequency selectivity similar to volume holograms, but unlike them the photonic crystals have higher contrast distribution of the refractive index. The high contrast of changes of the refractive index and large thickness of the gradient photonic crystals allow us to hope for the low threshold for formation of non-linear effects.

• The development of nanotechnologies for structuring the optical materials with nanometer resolution, and the creation of high-performance computing systems open up the possibility of synthesizing full-aperture elements of nanooptics and nanophotonics with complex topology and significant subwave characteristic dimensions of the nanorelief.

The development of the technology of three-dimensional micro- and nanostructuring (such as the two-photon polymerization technique and the technology of refractive index modification by femtosecond laser radiation) allows us to generalize the well-known statement of the problem and the calculation of the two-dimensional function of the microrelief of ‘flat’ DOEs to three dimensions. This will allow, for example, to produce the desired change in the amplitude–phase distribution in the cross section of the beam without causing energy losses associated with the introduction of spurious diffraction orders to bring the complex transmission function of the ‘two-dimensional’ DOE to the purely phase form. It is interesting to note that the technology of computer-controlled nanostructuring, successfully used for synthesis of diffractive optical elements, is also used to create optical metamaterials and photonic crystals and quasicrystals with the predetermined spectral properties. In this sense, the advantage of such technologies in comparison with the so-called group technologies (technologies based on self-organization, sol-gel processes, etc.) is obvious, since the computer-controlled nanostructuring allows the creation of optical metamaterials with pre-calculated parameters .

• To adequately describe the sharp focusing of laser radiation with overcoming of the diffraction limit, it is important to develop effective methods of non-paraxial vector modelling of radiation on the basis of the Rayleigh–Sommerfeld and Richards–Wolf integral expressions, or on the basis of an integral expansion of the light fields on the plane waves with the use of the fast Fourier transform algorithm. Improvement of the integrated methods of diffraction theory allows to effectively simulate the propagation of light in the near-field zone with input from the decaying evanescent waves; to simulate the use of DOE in focusing microscopic systems to form distributions in the focal region with the specified spatial and polarization properties and imaging microscopic systems to increase the resolution (and achieving super-resolution) using nanostructured microoptics.

• Development of the theory of vortex laser beams and their use for optical trapping and manipulation of micro- and nano-objects should be aimed at improving the energy efficiency of formation of the annular intensity distribution of the vortex laser beam in the focal plane. It is known that to improve the efficiency of optical trapping and retention of micro-and nano-particles in a light ring it is required to increase the energy density or decrease the diffractive thickness of the light rings. The size of the focal spot or diffractive thickness of the light rings can be reduced by the use of radially polarized light. Radially polarized beams are formed, for example, by subwavelength DOEs the fragments of which are subwavelength diffractive gratings. After passing through these gratings the electric field vector rotates at a certain angle. Therefore current research is focusing on the vector non-paraxial vortex beams with radial or azimuthal polarization.

There remains a pressing task of improving numerical methods of diffractive nanophotonics.

• Development of hybrid computationally efficient schemes numerical solutions of Maxwell's equations, which combine a rigorous approach to solving the problems of diffraction (FDTD method) on optical nanostructures and various approximate methods of solutions in the areas whose characteristic dimensions exceed the wavelength.

• Study of the propagation of electromagnetic pulses through the FDTD method. Calculation of the diffraction relief of optical elements for controlling the amplitude and phase characteristics of the pulses. Application of the method of numerical solution of Maxwell's equations for the study of propagation of radiation in non-linear media, in particular the study of the formation and interaction of solitons in photorefractive crystals under the influence of an external electric field.

• Recording of difference equations, more precisely taking into account the physics of the processes: on the grid areas corresponding to the geometric characteristics of the studied elements and the characteristics of the incident wave; for the areas of sparse on homogeneous areas and dense at the borders sections of media in accordance with the topography of such boundaries; on moving areas, taking into account the spatial localization of the electromagnetic pulse.

• Synthesis of specialized vector algorithms for the calculation of the diffraction pattern on parallel computing devices.

Note that all of the practical results of this book relate to the optical wave range but the methods developed can also be used for X-rays, which certainly requires a large amount of additional research.

The solution of these and other problems of the diffractive nanophotonics is the aim of the efforts of the authors at the present time.