Preface

The first publication about the discovery of diffraction grating by the American astronomer D. Rittenhouse dates back to 1786. It was not noticed by the scientific community of the day, and in the history of science the optician J. Fraunhofer was considered to be the creator of the diffraction grating (1821). Theoretical studies of this device, characterized by amazing dispersion properties were started by F.M. Schwerd in 1835. In those days, spectral analysis was coming into being. The needs from this new area stimulated making gratings with progressive enhancement of the resolution, and they encouraged relevant theoretical and experimental studies. The outstanding achievements of H.A. Rowland must be mentioned here. He developed a machine capable of making quite fine diffraction gratings (1882). Also, he suggested making ruling lines on a concave spherical surface and as a result spectrum dispersion and sharpness were elevated to a level that had not been seen before.

The progress in several scientific and technological fields is to a large extent guided by the performance of the presently available gratings which are so sophisticated that sometimes they seem to have little to do with their predecessors from the 19th century. Polarization converters and phase changers, filters and multiplexers, quantum and solid state oscillators, open quasi-optical dispersion resonators, and power compressors – these are only a few applications of periodic structures, which astonish us (up to now!) by their capabilities for controlled polarization, spatial and frequency selection of signals.

Different operating frequency ranges call for gratings differing in characteristic size (length of a period), and in their way of achieving the operating mode. The range is so wide that, say, if one end is a standard echelette optical reflection grating (3600 lines per millimeter on a 40 [cm] $\times$ 40 [cm] aluminium sheet) the other could be the antenna array of the unique decameter radio telescope UTR-2 developed and fabricated by the academician S.Ya. Braude's team at the Institute of Radio Physics and Electronics of the Ukrainian Academy of Sciences in 1966. This antenna field is developed by two multicomponent arrays. The first one, 1800 [m] long and 53 [m] wide, consists of 1440 wideband components making up 6 meridian aligned rows. The other, 900 [m] long and 40 [m] wide, is normal to the first one and carries 6 rows of 600 dipoles. All the dipoles (8 [m] long and 1.8 [m] across wire cylinders) are horizontally arranged at a height of 3.5 [m] and east–west oriented.

Few countries could afford equipment for ruling optical gratings with thousand lines per millimeter. This process, expensive and time-consuming, failed to satisfy growing practical requirements. Rather good results have been achieved in making replicas of mechanically produced originals. An idea that diffraction gratings can be manufactured with the aid of holography was suggested by Yu.N. Denisyuk in 1962. The idea has been developed into holographic gratings intensively used in the making of spectral instruments. The advantages of holographic gratings consist in the fact that such gratings are free from grating ghosts (i.e., high orders caused by periodicity deviation), they are characterized by little occasional light diffusion and are easy to produce. Naturally, to get desired diffraction characteristics from holographic gratings is more difficult than, e.g., getting them from ruled echelette gratings whose geometry uniquely depends on the so-called blaze angle. Holographic gratings rank below ruled gratings in diffraction efficiency but, according to many authors, their wavefront quality in a working order (harmonic) is better. In addition, several observation were made in the 1980s that the employment of certain schemes of hologram recording and subsequent photoresist processing opened the way for design of blazed gratings, including echelettes.

Evidently effective employment of diffraction gratings cannot be achieved without thorough theoretical and experimental research into their diffraction properties. The investigations began early in the 20th century. R.W. Wood improved the diffraction grating by shaping the grooves to specific geometries. On this basis, he launched systematic studies of the energy distribution among different harmonics and experimentally found the property of anomalous scattering. Lord Rayleigh was the first to expand the field scattered from the grating into a series of plane waves. Studying the echelette wave diffraction in theoretical terms, he developed an approximate technique (known as the Rayleigh method) which has been one of the most widely used until rigorous techniques became available.

In the evolution of grating theory, one can identify several key periods. One falls within the last decades of the 20th century, characterized by the fact that relevant theoretical problems were approached using classical mathematical disciplines: mathematical physics, computing mathematics, theory of differential, and integral equations, etc. That the grating became a subject of adequate mathematical simulation has opened up new opportunities for reliable physical analysis and also new avenues of attack, on a rigorous theoretical base, on numerous applied problems. At this stage, the modern electromagnetic theory of gratings was greatly contributed by the scientific schools of Marseille, France (R. Petit, D. Maystre, M. Neviere, P. Vincent, A. Roger, J. Chandezon, et al.) and Kharkov, Ukraine (V.P. Shestopalov, L.N. Litvinenko, S.A. Masalov, V.G. Sologub, A.A. Kirilenko, et al.). The key chapters of the book largely proceed from their achievements from the early 1960s and onwards. Obviously, the growth of the research in the above-mentioned schools was heavily influenced by the results from other scientific centers the world over. We will address the most significant of them.

The methodology of modern radio physics is based on mathematical simulation and numerical experiment and it is realized by solving boundary value (frequency domain) and initial boundary value (time domain) problems for Maxwell's equations. Time domain approaches (see, e.g., Chapter 4) offer more versatility and are more suited for the analysis of sophisticated electromagnetic structures of interest for applications. As a rule, the calculations here are reduced to implementation of explicit schemes (the schemes with the sequential passage of the time layers). There is a good agreement between the calculated results (results from analysis of electromagnetic field space–time transformations) and general human perception – the time domain is free of some idealizations, which are peculiar to the frequency domain. Moreover, time domain results are easy to change into the amplitude–frequency characteristics in the prefixed range of the frequency parameter $k = 2\pi / \lambda$, where λ is the free space wavelength. However, time domain methods are not used as extensively as one would expect for getting physical results proper. Thus, for example, all power of the most popular at the moment FDTD-method is mainly applied to solution of particular engineering problems.

Far more examples of systematic and fruitful theoretical treatments can be met in time harmonic electromagnetics whose problems have been addressed much earlier in rigorous formulation. The last decades of the 20th century have brought some special powerful techniques for analysis and synthesis of various electromagnetic objects. Numerous physical phenomena accompanying processes of monochromatic wave's radiation, propagation, and scattering have been identified, interpreted, and implemented into design of novel devices. Such advances have been assured by the fact that new theoretical methods have been developed being oriented to the solution to the specific applied problems. They have accounted the peculiarities of problems of interest and hence have provided with not only quantitative information, but they created also the base for qualitative analysis with further generalization. As an example, one may consider the authentic analytic regularization procedures (see Chapter 2) outperforming other frequency domain techniques in resonance situations. Actually, nearly all profound physical results gained from electromagnetic theory of gratings are due to usage of analytic regularization procedures.

The long-wave specific case ($\kappa = l / \lambda \ll 1$, l is the grating period length), ending up with solutions of simple analytic representations and convenient approximations, has been understood most comprehensively by frequency domain methods. Here, the approach grounded on equivalent boundary conditions possessing in the general case anisotropic properties is widely applied (B.Ya. Moyzhes, L.A. Vainshtein, V.M. Astapenko and G.D. Malyuzhinetz; Ye.I. Nefedov, and A.N. Sivov, et al.). The theory of dense gratings based on this approach takes into account the influence of shape and relative size of grating's elements, the presence of sharp boundaries in the dielectric filling and allows one to make a correct limit transition as the conductors come infinitely close. A key point in the solution of the diffraction problem based on this theory is a search for the reflection and the propagation coefficients in terms of powers of a small parameter κ via considering a relevant static problem. The long-wavelength diffraction is implemented in many modern superhigh-frequency devices and units, thus the relevant theoretical studies are of current importance.

Simple and convenient analytic representations are very useful for the designers and, at the same time, they are an aid to general nature interpretations contributing to the electromagnetic theory of gratings. An example is the effect observed by G.D. Malyuzhinetz in the 1940s: given a certain angle of incidence on a dense grating arranged by metal bars of nonzero thickness, a plane H-polarized wave propagates through it with no reflection.

Of tremendous interest for physics and applications and a great problem for analysis is the resonance case $\kappa = O(1)$, i.e., the case when the wavelength is comparable with the grating period. When computer resources were limited, the research into the resonance domain had been restricted to some specific or limiting situations. They were studied by V.S. Ignatovskiy, E.A.N. Whitehead, F. Berz, J.F. Carlson, A.E. Heins, G.L. Baldwin, L.A. Vainshtein, V. Twersky, Yu.P. Lysanov, and others. These researchers laid a solid ground for the modern theory of resonant wave scattering by periodic structures. Indeed, the ideas and achievements gained in the 1940s–1960s are traced in almost every present-day method of mathematical modeling oriented to the numerical experiment. First of all, it is the method of partial domains (or mode matching method) whose first fruitful implementation can be seen in L.N. Deryugin's works. Next are the potential-theory-based methods (integral equation techniques) whose today's technique (N. Amitay, V. Galindo, and C.P. Wu; A.S. Il'inskiy and T.N. Galishnikova; A.I. Sukhov; Z.T. Nazarchuk, and others) is based on quasi-periodic Green's function derived by V. Twersky. At a point of equivalent reformulation of the original boundary value problem, the authors of some analytic numerical methods (Ye.V. Avdeev and G.V. Voskresenskiy; R. Mittra and T. Itoh; S.M. Zhurav, and others) address, either implicitly or not, to the technique and the results of the analytic solution to canonic diffraction problems similar to those considered by E.A.N. Whitehead, F. Berz, and others. Only few such problems have been solved rigorously. The most popular ones (see, e.g., works by E. Luneburg and K. Westpfahl; V.D. Luk'yanov; L.A. Vainshtein and V.I. Vol'man) have always been those about half-plane gratings and planar strip gratings. The enduring interest in elementary structures whose diffraction characteristics have long been thoroughly studied for arbitrary geometrical parameters and frequencies, from the long to the short wave regions, is indeed reasonable. The main significance of these considerations and the most valuable aspects of the outcomes consist in the search for new ideas and approaches and proving their potentials to be used in more sophisticated situations, which are far from standard.

In closing the issue of succession, it should be mentioned that the numerical solution of the problems concerning the plane wave diffraction by periodic corrugated surfaces has been the most frequently attempted by invoking the Rayleigh method (Rayleigh hypothesis). There are methods that take the Rayleigh representations for the scattered field and extend them in a straightforward manner from their region of validity directly to the grating surface. Furthermore, there are methods, prompted by the Rayleigh hypothesis, but resting on the fundamental results of I.N. Vekua about completeness of some systems of functions on curved contours. In the first case, difficulties in the proof of the principal step (it is necessary to study singularities of the analytic continuation of the Rayleigh representation as a function of space coordinates) can be overcome only for shallow gratings, with groove profile described by a sufficiently smooth one-valued function (see works of A.G. Kyurkchan). And even then a correct truncation of the resulting infinite system of algebraic equations for unknown amplitudes of the field space harmonics is not possible. In the other case, a principal feasibility exists to construct special linear combinations of functions that are asymptotically close to the solutions of the corresponding diffraction problems throughout the whole scattering domain. The central problem – development of stable computation schemes – is solved then with the adaptive (assignable by the groove shape and κ value) collocation technique.

In many works of electromagnetic theory of gratings the modern scientific methodology chain "object → mathematical model → algorithm → numerical experiment → physical interpretation of the results → formulation of general conclusions and recommendations" breaks somewhere in the middle, at a level of standard illustrations of the efficiency of the algorithm. But nevertheless, after L.N. Deryugin's work who analyzed (in terms of some particular cases) the surface and double surface resonances on the comb gratings, issues do appear, which inform of experimental, analytic, and numerical results, concerning

- threshold phenomena (A. Hessel and A.A. Oliner; B.M. Bolotovskiy and A.N. Lebedev; E.A. Yakovlev and M.V. Robachevskiy);
- semitransparent grating effects of total resonant transition and reflection of plane waves (Ye.V. Avdeev and G.V. Voskresenskiy; A.F. Chaplin and A.D. Khzmalyan; R.S. Zaridze and G.M. Talakvadze; Yu.P. Vinichenko, A.A. Lemanskiy, and M.B. Mityashev);
- effects of total nonspecular wave reflection by reflective structures (E.V. Jull and G.R. Ebbeson; J.R. Andrewarsha, J.R. Fox, and I.J. Wilson; S.N. Vlasov and Ye.V. Koposova; and others).

Some authors (see, for example, works of E.V. Jull, D.C.W. Hi, N.C. Beaulieu, and P. Facq) have raised a very important question about the differences between the ideal (infinitely extending structure in the plane wave field) and actual (finite excitation field spot on the infinite periodic structure or finite structure in the plane wave field) operating modes of the grating.

Also nowadays the diffraction grating is still one of the central objects of electromagnetic analysis. Independent of how comprehensive the progress in our understanding of the grating is, continued research in this direction remains very important, indeed practical needs and the intrinsic logic of development of the modern grating theory present us with new problems, sending us to seek and hopefully find ways to their solution. Just so was formed during the recent years a new line of investigation, which is partially considered in this book (see Chapter 5) and associated with the analysis, synthesis, and determination of equivalent parameters of artificial materials – layers and coatings, which have a periodic structure and properties exhibited by natural materials in exceptional cases only.

Generally speaking, the book reflects those results which, in our opinion, are able to further pursue electromagnetic theory of gratings in pace with today's requirements of fundamental and applied science. The book gives the reader quite a comprehensive idea of:

- spectral theory of gratings (Chapter 1) giving reliable grounds for physical analysis of space–frequency and space–time transformations of the electromagnetic field in open periodic resonators and waveguides;
- authentic analytic regularization procedures (Chapter 2) that, in contradistinction to the traditional frequency domain approaches, fit perfectly for the analysis of resonant wave scattering processes;
- parametric Fourier method and C-method (Chapter 3) oriented on the effective numerical analysis of transformation properties of periodic interfaces and multilayer conformal arrays;
- new rigorous methods for analysis of spatial–temporal transformations of electromagnetic field that are grounded on the construction and incorporation into the standard finite-difference computational schemes, the so-called exact absorbing boundary conditions (Chapter 4);
- new solution variants to the homogenization problem (Chapter 5) – the central problem arising in the synthesis of metamaterials and metasurfaces;
- new physical and applied results (Chapters 2–5) about pulsed and monochromatic wave resonant scattering by periodic structures, including structures loaded on dielectric layers or chiral and left-hand medium layers, etc.

The authors hope that the reader will find that the discussed physical and applied results are presented in an illuminating way. Thus, for example, some figures in Chapter 4 are accompanied by **.exe** files which enable to watch in dynamics the space–time transformations of the electromagnetic field close to finite and infinite periodic structures. The archive with these files is open for downloading at http://www.ire.kharkov.ua/downloads/Figures_EXE_Files.zip.

The book is intended for researchers and graduate students in computational electrodynamics and optics, theoretical and applied radio physics. The material is also suitable for undergraduate courses in physics, computational physics, and applied mathematics.

The authors are representatives of a series of large European scientific and educational centers: Royal Institute of Technology, Stockholm, Sweden (Staffan Ström, the editor and the co-author of Chapter 4); *Blaise Pascal* University, Clermont-Ferrand, France (Jean Chandezon and Gerard Granet – Chapter 3); *Usikov* Institute of Radio Physics and Electronics of the National Academy of Sciences of Ukraine, Kharkov, Ukraine (Petr Melezhik – Sections 2.2, 2.4, 2.5; Anatoliy Poyedinchuk – Sections 2.1, 2.2, 2.4, 2.5, 3.6; Yury Sirenko – the editor, the author and co-author of Chapters 1, 4, and Section 2.3; Yuriy Tuchkin – Sections 2.1, 2.6; and Nataliya Yashina – Chapter 4 and Sections 2.4, 2.5, 3.6); Lund University, Lund, Sweden (Daniel Sjöberg – Chapter 5).

In this book, they are united by their profound interest in periodic structures, an area whose study has always been associated with burning scientific and engineering problems for the last one and a half hundred years.

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