HISTORY OF WIRELESS
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HISTORICAL BACKGROUND AND DEVELOPMENT OF SOVIET QUASIOPTICS AT NEAR-MILLIMETER AND SUB-MILLIMETER WAVELENGTHS

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15.1 INTRODUCTION

This article reviews the history and state-of-the-art of quasioptical systems based on various transmission-line technologies. We trace the development of quasioptics back to the very early years of experimental electromagnetics, in which this was pioneering research into "Hertz waves". We discuss numerous applications of quasioptical systems in the millimeter (mm) and sub-millimeter wavelength ranges. The main focus is on the work of scientists and engineers of the former USSR whose contribution to quasioptics is relatively little known by the world electromagnetics community.

15.2 QUASIOPTICS IN THE BROAD AND NARROW SENSE

After more than a century of its history, quasioptics (QO) can be considered to be a specific branch of microwave science and engineering. However, what is QO? Broadly speaking, this term is used to characterize methods and tools devised for handling, both in theory and in practice, electromagnetic waves propagating in the form of directive beams, whose width w is greater than the wavelength λ, but which is smaller than the cross-section size, D, of the limiting apertures and guiding structures: $\lambda < w < D$. Normally $D < 100\lambda$, and devices as small as $D = 3\lambda$ can be analyzed with some success using QO. Therefore QO phenomena and devices cannot be characterized with geometrical optics (GO) that requires $D > 1000\lambda$, and both diffraction and ray-like optical phenomena must be taken into account. It is also clear that, as Maxwell's equations (although not material equations) are scalable in terms of the ratio D/λ, the range of parameters satisfying the above definition sweeps across all the ranges of the electromagnetic spectrum, from radio waves to visible light (Figure 15.1) and beyond. Therefore QO effects, principles and devices can be encountered in any of these ranges, from skyscraper-high deep-space communication reflectors to micron-size lasers with oxide windows. A good example of a universal QO device is the dielectric lens that was first borrowed from optics by O. Lodge for his 1889 experiments at $\lambda = 101$ cm [1], then used in microwave and millimeter-wave systems in the 1950-80s, and is today experiencing a third youth in terahertz receivers. Moreover, as the above relation among the device size, beam size, and wavelength is common in today's optoelectronics, it is clear that QO principles potentially may have a great impact on this field of science as well. Nevertheless, in the narrow sense, the term QO relates to the devices and systems

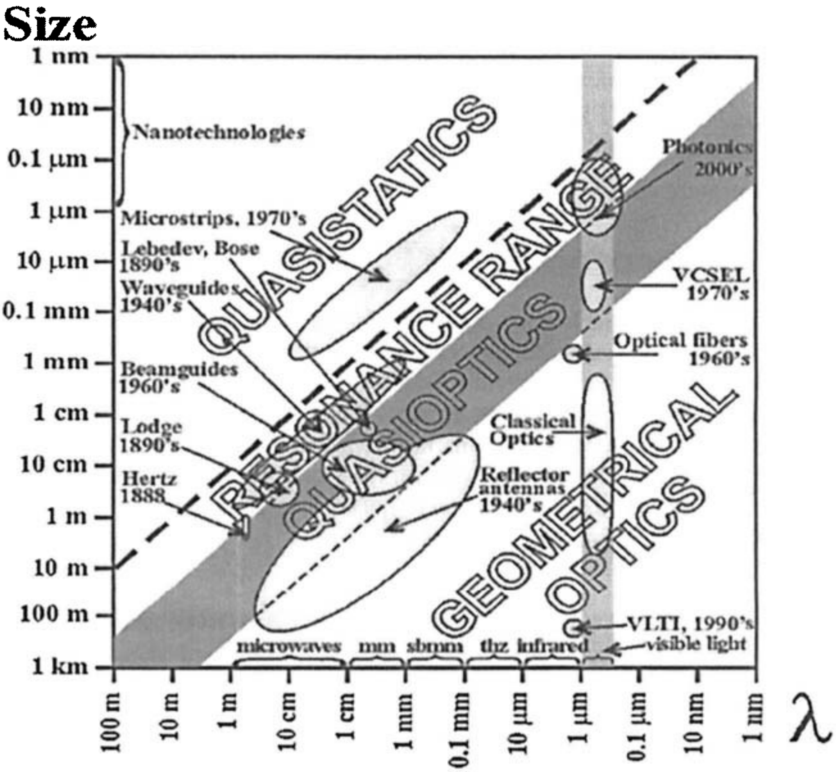


Figure 15.1. A diagram showing the place of quasioptical (QO) techniques with respect to geometrical optic (GO) and quasistatic techniques, in the plane of the two parameters - device size and wavelength. The frequency ranges are also indicated, as well as major related technologies and the dates of their emergence. The resonance range corresponds to device sizes between a fraction of a wavelength and several wavelengths.

working with millimeter (mm) and sub-millimeter (sub-mm) waves. F. Karplus apparently coined the term *quasioptics* in 1931 [2], and then it was forgotten for exactly 30 years before being used again in [3]. A parallel term *microwave optics* can be traced, however, in several remarkable books and review articles of the 1950–1960s [4-10] and others.

If compared with the classical optics of light, mm and sub-mm wave QO has certain characteristic features: here, electromagnetic waves display their coherence and definite polarization state, and they also display much greater divergence and diffraction, while direct measurements of their amplitude and phase are relatively easy.

It is difficult to find a publication in which the various historical aspects of QO are presented in a complete manner, tracing the development of this field and including an account of specific features of particular scientific problems and applications. A significant early Western publication dealing with QO is the collection of papers presented at the *International Symposium on Quasioptics* held in New York in 1964 [11]. It was L. Felsen, one of the organizers of the symposium, who should be credited with firmly establishing this term. Since then, several papers [8, 12-17] containing detailed reviews of QO principles and major applications have appeared. A book focusing on selected applications was published in 1990 [18]. In 1998, a comprehensive monograph [19] appeared, with a bibliography containing more than 700 titles. In this book, the theory of Gaussian wave beams is presented in a systematic way, together with the results of development of corresponding QO components. Here, specific solutions to many practical problems were considered, based on this important but not unique way of transmitting electromagnetic power and designing various functional systems. However, almost all of the referenced material was of Western origin.

Beginning in the early 1960s, active research and development into QO was undertaken in the USSR. There was a good background for this development: one of the most important mm-wave pioneers was Piotr N. Lebedev (1866–1912), who worked at Moscow University from 1892 to 1911 (Figure 15.2). Later, magnetrons were developed in many civil and military laboratories in the 1920–1940s. After World War II, the government of the USSR considered microwave radar to be the third most important defense

Figure 15.2. Piotr N. Lebedev in the 1900s.

technology, after nuclear weapons and intercontinental missiles. As we shall see, research into QO was done mainly in the laboratories of the USSR Academy of Sciences (now, Russian Academy of Sciences – RAS, and the National Academy of Sciences of Ukraine – NASU) located in three cities: Moscow, Nizny Novgorod, and Kharkov. It should be noted that the USSR microwave researchers always had good access to the Western scientific literature. However, after the late 1930s their papers were almost never published in international journals. Even if not classified, papers by Soviet scientists having a practical orientation had little chance to reach Western readers except through translations of Soviet journals having limited accessibility. Participation in conferences outside the USSR was virtually impossible.

The present article is thus an attempt to review the little-known QO technologies of the USSR based on the various transmission lines used, along with their numerous applications. Here, we have used several sources of information including useful reviews of the history of microwaves [20-23]. The 1960s were the "golden age" of QO, during which excellent reviews [24, 25] were published. Special credit should be given to the book [26], which contained comprehensive information on QO transmission lines of various types, and on the system design principles that corresponded to the components available in the USSR in the late 1960s. Additional information about the later developments based on hollow dielectric beam waveguides and metal-dielectric waveguides can be found in [27, 28]. We have also used interviews with the staff of R&D laboratories and reviewed formerly classified technical reports.

In order to make the proper positioning of the accomplishments of the Soviet scientists easier, we shall review them against the background of their Western counterparts. The basic idea of this review is to follow the development of QO transmission lines. Here, the following important topics will be touched only marginally: open resonators, filters based on various frequency-selective screens, diplexers and multiplexers, stabilization of solid state sources, power combining, power measuring devices of the absorption type, and cryogenic receivers. We shall mainly compare the characteristics of different types of transmission lines, and the opportunities for development of standard components, rather then consider specific devices and instruments. Nevertheless, we shall try to show major trends in research and development, and to emphasize the basic books, papers, and reviews in this field.

We shall begin with a brief survey of research into "Hertz waves" in the 1890s. This term was introduced by a handful of scientists who followed H. Hertz, carrying out early experiments with short electromagnetic waves. In fact, at that early stage they had already established all the fundamental QO principles, which were so widely and efficiently used in mm-wave technology 70 years later.

15.3 PIONEERING RESEARCH INTO THE "HERTZ OPTICS" (1888–1900) AND LEBEDEV'S CONTRIBUTION

The shaping of QO as a scientific field is closely tied to the early history of wireless communication. It was triggered by Hertz's famous experiments, which he presented on December 13, 1888 in the lecture "On the rays of the electrical force" at the meeting of the Berlin Academy of Sciences. In this presentation, Hertz convincingly proved that the nature of electromagnetic and light waves is identical [29].

When performing his experiments, Hertz tried to make the dimensions of the devices as small as possible: however, he still followed classical optical principles. Hertz used electromagnetic radiation with a wavelength of $\lambda = 66$ cm. "I succeeded," – he had written, – "to obtain the well-observable rays of the electrical force and to perform with their aid all the elementary experiments which are produced with light and heat rays". To concentrate electromagnetic power in a directive beam, Hertz had employed a parabolic cylindrical reflector made from a zinc sheet with an aperture of 2 m by 1.2 m and a focal distance of 12.5 cm (Figure 15.3). He placed a dipole at the reflector focal line, with a spark gap for connection with an induction facility of the Kaiser-Schmidt type (Figure 15.4a). The design of the receiving antenna was analogous, and a resonator in the form of two metal rods was placed at the reflector focal line. The internal ends of the rod were joined by wires passing through the reflector, and a micrometer screw was employed to regulate the spark gap (Figure 15.4b). The electromagnetic radiation was detected through the secondary spark discharge.

It is extremely impressive that although his "beam" and reflector were only 2 wavelengths in size, Hertz was able to confirm the laws of propagation, reflection and refraction formerly attributed only to "optics". He also studied polarization phenomena with reference to electromagnetic waves. Thus, in fact, he used for the first time all the QO principles that were to be employed in the

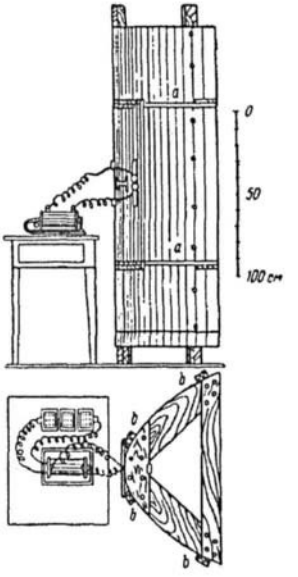


Figure 15.3. The parabolic reflector of Hertz's antenna used in experiments of 1888 with waves of $\lambda = 66$ cm (reproduced from [29]).

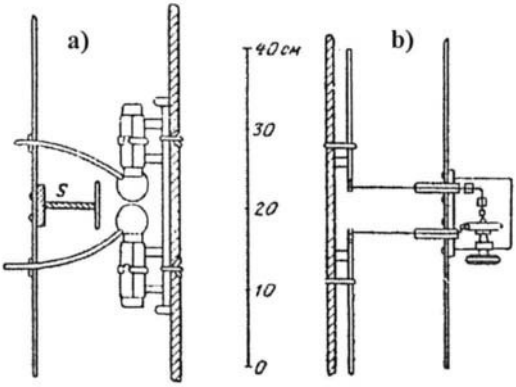


Figure 15.4. a) Transmitting and **b)** receiving dipoles of Hertz's antenna (reproduced from [29]).

future for microwave engineering, with the exception of, probably, a lens. His screens were made from tin foil, gold sheets, and wooden shields. To investigate the refraction of the beam passing from one medium to another, Hertz made a prism two wavelengths in size from asphalt having a mass of 1200 kg. Its cross section was that of an isosceles triangle having a base of 1.2 m, a height of 1.5 m, and an angle of refraction of 30°. In the polarization experiments he used a grating made from copper wires (diameter = 1cm, period $p = 3$ cm, thus $p = 0.05\lambda$) stretched across an octagonal wooden frame 2 m by 2 m (i.e., 3λ by 3λ) in size.

Hertz's experiments had fundamental significance and stimulated research into "optical" properties of electromagnetic waves and their practical applications. Hertz's followers, when reproducing and extending his experiments, tried to use shorter wavelength radiation, so as to improve the performance of the various components.

In 1894, A. Righi in Italy modified the Hertz dipole by introducing three spark gaps instead of a single one. This enabled him to obtain radiation with wavelengths $\lambda = 7.5$ and 20 cm [30]. One of his oscillators with a parabolic reflector is shown in Figure 15.5.

Waves of considerably shorter wavelength, $\lambda = 6$ mm, were experimentally studied in 1895 by P. Lebedev in Russia [31]. As he explained, "there appeared a need to make his (Hertz's) experiments on a smaller scale, more handy for scientific research". The turn to such short wavelengths was necessary to form and focus the "rays of electrical force" in the experiments on the interaction of electromagnetic waves with materials. Though in general, Lebedev's research program corresponded to Hertz's experiments, the dimensions of components developed by him were 100 times smaller and their technical realization at the time being was unique and was admired by his contemporaries. The primary radiator was a development of the idea proposed by Righi and consisted of two platinum cylinders 1.3 mm in length and 0.5 mm in diameter, placed at the focus of a circular-cylindrical reflector having an aperture

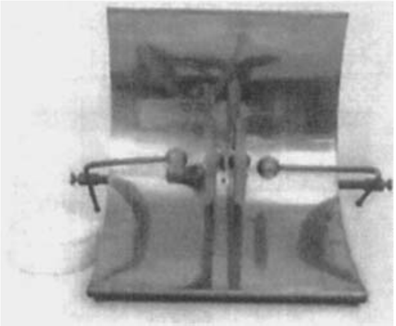


Figure 15.5. The design of one of Righi's oscillators with a parabolic reflector used in 1894 (reproduced by permission of the Museum of Physics, University of Bologna).

2 cm by 1.2 cm in size. The reflector was immersed in a tank filled with kerosene; the electromagnetic beam emerged from it through a mica window. The receiving antenna was made similarly: two straight-wire resonators 3 mm long were placed at the focus of the secondary reflector, where the indicator was not a secondary spark as it was for Hertz, but an iron-constantan thermocouple and a galvanometer which monitored the temperature rise and thus the incident power. In most of the experiments the distance between antennas was 10 cm.

The set of experimental components (Figure 15.6) developed by Lebedev included a wire polarizer (a grating of 20 thin wires tightened over a rectangular frame with dimensions of 2 cm by 2 cm), metallic reflectors of 2 cm by 2 cm, an ebonite prism (1.8 cm height, 1.2 cm base, angle of refraction 45°, 2 gram weight), and a quarter-wavelength phase-shifting plate made from birefringent crystals of rhombic sulphur. Thus the components made by Lebedev had dimensions of 2λ to 3λ, i.e. very similar to those of Hertz for longer waves. Besides reproducing Hertz's results, Lebedev's experiments enabled him, for the first time, to observe birefringence in anisotropic media, leading him to the conclusion of "the identity between the phenomena of the electrical oscillations and light in this more complicated case". Moreover, when taking a smaller wire radiator of length 0.8 mm and diameter 0.3 mm, Lebedev observed oscillations at a wavelength $\lambda = 3$ mm [32]. At the time these were the shortest electromagnetic waves obtained using an oscillating spark discharge. Lebedev's experiments anticipated the future development of QO methods for forming narrow directive beams and their transformation in various mm-wave systems. He wrote in 1895: "The short waves are promising in numerous applications because here, by using devices of moderate size and perfect in an optical sense, one can easily neglect diffraction phenomena, and very small quantities of the materials to be studied are quite sufficient for accurate measurements. Therefore, relatively simple experimental requirements common in optical research can be realized with the Hertz waves as well." [31]. Thus, we may state that in addition to his more widely known reputation of absolute pioneer in the experimental verification of the pressure of light on material obstacles, Lebedev was also an insightful pioneer of millimeter waves. In a letter to Lebedev dated 10.10.1899, A. Dubois

Figure 15.6. The components designed by P. Lebedev for his Hertz-type experiments at the wavelength λ = 6 mm in 1895 (reproduced from [31]).

wrote that, as a result of his work, "Russia becomes the world's small wave champion" [33]. This was not completely true as J. C. Bose in Calcutta, India, was already systematically experimenting with waves as short as λ = 5 mm [34, 35].

One of the most challenging areas was developing new radiating and receiving devices. In 1894, O. G. Lodge was the first to propose a waveguide-type feed by placing a wire radiator inside a section of a circular copper pipe closed at one end and open at the other (Figure 15.7). In his experiments he used electromagnetic waves of λ = 7.5 and 20 cm [36]. In 1897, analogous feeds based on open pipes of circular and square cross-sections were investigated by J. C.

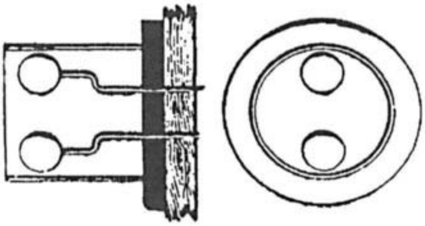


Figure 15.7. Lodge's waveguide radiator having the form of a section of a copper tube with circular cross-section used in 1894 (reproduced from [36]).

Bose in the range $\lambda = 0.5$ to 2.5 cm [34]. In the shorter wavelength portion of this range his "waveguide" was oversized (its transverse dimension was about 2.5 cm), and suppression of the higher-order modes was achieved by using an absorbing lining on the inner surface of the tube. The absorber was blotting paper dipped in an electrolyte. In 1900, in his research with waves of $\lambda = 20$ cm, J. A. Fleming proposed a rectangular-box feed [37], which can be considered to be a prototype of the rectangular open-end waveguide feed. He also employed a cylindrical lens made from paraffin for beam focusing (Figure 15.8a). In systems based on waveguide-section feeds, the investigators had used the filtering properties of the waveguide to suppress the low-frequency components of the broadband noise-like spectrum of the radiating source.

The possibility of concentrating electromagnetic power by using lenses attracted many early researchers as an alternative to reflector systems, which are not always convenient in laboratory situations. At first, in 1889, Lodge and G. Howard [1] used cylindrical lenses made from pitch. However they failed to achieve sufficient beam focusing because the lens size was smaller than the wavelength ($\lambda = 101$ cm). When in 1894 Lodge used a glass lens with a diameter of 23 cm for $\lambda = 7.5$ cm ($D = 3\lambda$), he immediately marked a noticeable focusing effect. Even greater focusing was found in Righi's experiments [38] with lenses (Figure 15.9) fabricated from paraffin and sulphur, having a diameter of 32 cm used at $\lambda = 3$ cm ($D = 10\lambda$). In 1897 Bose carried out very interesting experiments in the wavelength range between $\lambda = 5$ mm and $\lambda = 2.5$ cm [34]. He developed a number of QO devices including a shielded lens antenna (Figure 15.10), in which a feed and a cylindrical sulfur lens having 25 mm diameters

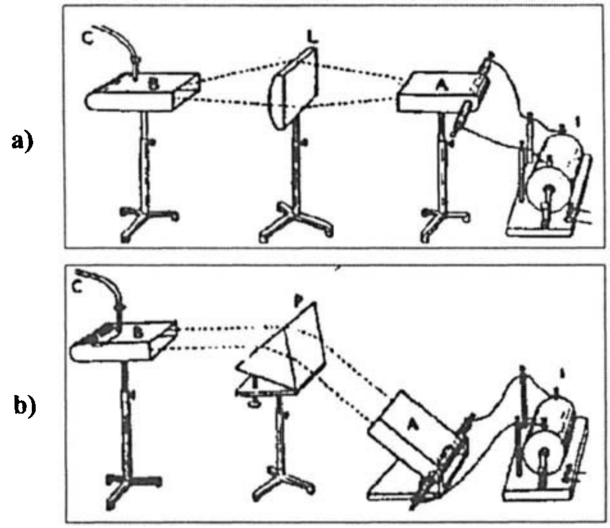


Figure 15.8. Fleming's experimental facilities in 1900 for the wavelength of $\lambda = 20$ cm: **a)** Radiator designed as a rectangular waveguide with a cylindrical focusing lens, **b)** Measurement facility for studying the refracting properties of a prism (reproduced from [37]).

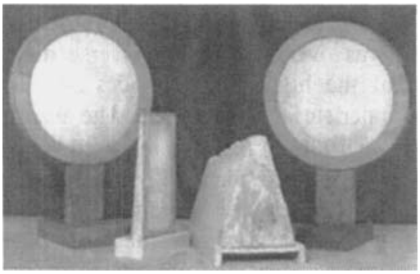


Figure 15.9. Lenses made from sulfur used in Righi's 1897 experiments (reproduced by permission of the Museum of Physics, University of Bologna).

were combined in a single unit within a tube. To avoid undesirable multiple reflections, he used an absorbing lining at the tube inner surface, similar to that in his waveguide radiators. In addition, Bose was the first to employ a pyramidal waveguide horn as a receiving antenna [39].

As early as 1890, E. Branly proposed a detector based on the variation of conductivity of metallic powder under electromagnetic-wave illumination. Subsequently, most researchers used various versions of a similar device improved by Lodge in 1894 and named by him a "coherer". Bose also made a great contribution to the development of detecting devices. Trying to raise their reliability and stability, he modernized the coherer by using a spiral steel spring instead of metallic powder [34, 39]. Such a device was in fact a multicontact detector exploiting the semiconductor properties of the natural oxide coating of the spring. The detector design enabled one to control the sensitivity, allowing Bose to perform quite precise measurements with high reliability. His follow-on research on the conductivity of a number of materials under electromagnetic-wave illumination brought him to the development of a point-contact semiconductor detector based on lead sulfide. Bose's invention was registered in 1901 and later was recognized as the world first patent for a semiconductor device (dated March 29, 1904 [40]) [41]. This was, in fact, a QO device designed for experiments in the mm wavelength range. The point-contact detector (cat whisker) was located in a spherical case, and electromagnetic radiation was incident through a glass lens (Figure 2.33).

Together with the development of new radiating and detecting devices, researchers in the 1890s worked with other QO components. In particular, Lodge

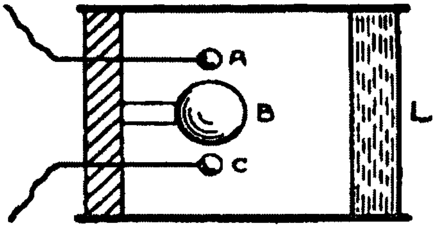


Figure 15.10. The design of Bose's shielded lens antenna of 1893 (reproduced from [34]).

[36] and Fleming [37] studied the refracting properties of paraffin prisms (refer back to Figure 15.8b). A possibility to control, over a wide range, the value of the ratio of the transmitted power to the reflected power by varying the distance between the faces of two dielectric prisms (Figure 15.11) was first noted by Bose, and this property led him to the invention of an original attenuator [34]. An important step was the development of polarimetric and interferometric systems based on available components. By using an interferometer developed in 1897, G. Hall carried out a measurement of wavelength ($\lambda = 9.12$ cm) with an error less than 1% [43]. Bose had designed a spectrometer (Figure 2.29 and Figure 9.2), which used a set of QO devices [39] in the wavelength range of λ=5 mm to 2.5 cm. additionally, he had developed a number of polarimetric systems [43] in which he used both wire diffraction gratings and metal-plate periodic structures as polarizers (Figure 15.12). The period of the latter was chosen to provide a cutoff regime for the principal mode in a waveguide-type system.

Successful research into the "Hertz optics" at the turn of XIX and XX centuries had led to the emergence of new methods of investigation of materials. Bose applied his set of measurement facilities to study the polarization properties of many natural materials and artificial substances, including various crystals and vegetable fibers [43]. He also performed the first experiments on the microwave modeling of the molecules of some optically active substances [44]. Righi proposed a quarter wave plate [38] based on the polarization-selective properties of vegetable fibers. In 1894, A. Garbasso and E. Ashkenass made a polarization-selective reflector formed by an array of dipoles, and also a prism formed by a system of dispersive dipoles (λ = 7.4 cm) [45] that can be considered to be the first device made from an artificial dielectric. In 1894, M. Birkeland fabricated "synthetic" materials, in particular, "ferro-paraffin" which consisted of iron filings (or powder) mixed together with quartz powder in paraffin [46]. The properties of water and ice were examined at various frequencies (Fleming [37], Cole [47]), as well as those of alcohol, castor and olive oils, petrol, and other liquids (Branley [48]).

Being of great fundamental value, research on the "Hertz waves" had attracted the attention of many bright electrical engineers to investigate wireless

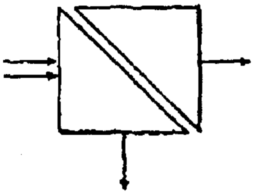


Figure 15.11. A design of Bose's attenuator based on two prisms with controlled clearance between faces of 1897. (reproduced from [34]).

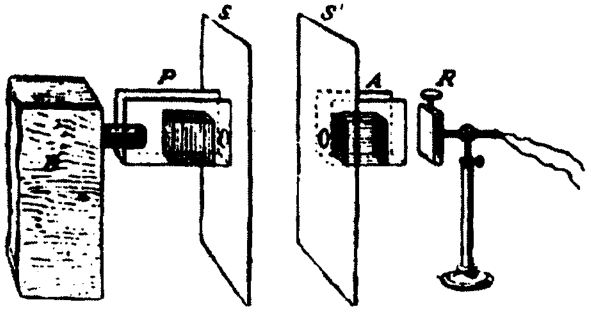


Figure 15.12. Bose's metal-plate polarizer used in 1895 (reproduced from [43]).

theory and technology, including G. Marconi, A. Popov, N. Tesla and others. In his early research Marconi was influenced by the work of his one-time teacher Righi, and used certain QO ideas of the latter. Thus, in his first trials on radiotelegraphy in 1894 Marconi employed a wavelength of 25 cm with a reflector antenna, to obtain a directive beam of radiation. This antenna [49] had the shape of parabolic cylinder (Figure 15.13) and enabled him to achieve communication over a distance of 6.5 km. A similar parabolic reflector, with a spark-gap oscillator, dipole feed, and coherer detector was used by the German engineer C. Hülsmeyer in his patent on "Device for detection of distant metal objects by using electric waves" (1904) [50]. This device was able to detect a boat by measuring the reflected signal: it was, in fact, radar. At that time, however, this invention did not attract the attention of the military, probably because of the small operating distance resulting from the small power of spark-gap oscillator and the low sensitivity of the coherer employed as the detector.

Research results obtained in 1888 to 1900 by using QO technologies had achieved the main goal of Hertz and his followers: they had proved that light and electromagnetic fields of other wavelengths had the same nature. Nevertheless, despite such a bright and promising start, in the following years, interest in both microwaves and QO methods diminished. Part of the reason was the available technology: the spark discharge oscillator approach was quickly exhausted in the effort to further reduce the wavelength of operation and to move to higher-frequency domains of research.

Lebedev was one of those who clearly realized that the development of monochromatic sources in the mm and sub-mm ranges would present the central and most complicated problem. It is worth citing his words written in 1901 [32]:

> *To obtain the waves between λ=3 mm and λ=0.1 mm, we must find a new source. To measure the lengths of these shorter waves by using interference and to observe them by a thermocouple will not pose any difficulty, however to obtain them by the already known ways is hardly possible; the wire*

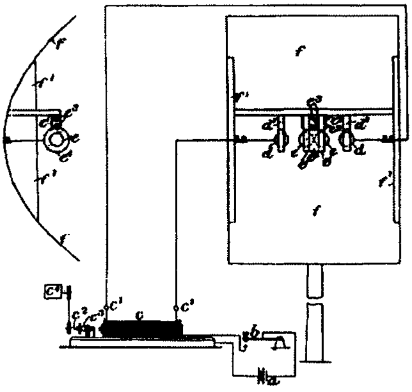


Figure 15.13. Marconi's antenna with a parabolic reflector (reproduced from [49]).

> *feed and resonator should be given the sizes such that if compared with them, the most perfect masterpieces of the watch-maker or jeweler would seem only clumsy metallic masses; the energy which could be accumulated on such a charged metallic wire would be negligibly small; moreover, it is absolutely unknown if it is possible to generate the waves by using a spark discharge of these negligible charges. Today we have no chance to foresee how we will succeed in solving this trouble; in any case, here we shall meet significant difficulties, and the technique of obtaining even shorter waves will be a very important step forward in the field of experimental physics.*

However, there was a more fundamental reason – "Hertz optics" did not initiate any immediate demand from industry, military, governments or the public. For example, *Telefunken* experts rejected Hülsmeyer's radar as useless, causing the author to switch to mechanical engineering. In contrast, the idea of making telegraphy wireless was easily understandable and clearly had fantastic potential. Although Marconi met rejection in Italy, both from the military and from the king's court, his successful demonstrations of long distance communication in England quickly convinced important UK government and industry customers. As early as 1901, Marconi had succeeded in establishing a radio link between Europe and America across the Atlantic, over a distance of 3500 km. In 1904 both sides of the Anglo-Boer War were already equipped with wireless telegraphy. This refocused the interest of researchers, for more than 30 years, from microwaves to short, medium and long radio waves having wavelength a factor of 100 to 100,000 times greater.

15.4 EARLY SUCCESS: FREE-SPACE GAUSSIAN-BEAM QUASIOPTICAL TECHNOLOGIES

The 1920s saw only isolated research efforts undertaken with short wavelength electromagnetic radiation. In 1923, E. Nichols and J. Tear used special version of the spark gap source and produced a 0.22 mm wavelength signal [51]. The next year, A. Glagolewa-Arkadiewa in Moscow also developed a special type of spark source, which included an induction coil and aluminum fillings immersed in mineral oil. The waves were radiated by wires located near the focus of a parabolic reflector and collected by a thermal detector at the focus of a second reflector. The range of wavelengths produced by this source covered the band from 50 mm to an amazingly short 0.082 mm [52].

Large-scale research and development into microwaves was renewed only in the late 1930s, when monochromatic oscillation sources, as well as the sensitive receivers and amplifiers had become available. Another major factor was the development of hollow metallic waveguides and corresponding components. As waveguide technology advanced to shorter wavelengths, the methods of fabricating components were also improved, new materials were created, and measuring devices and techniques were developed. For nearly 20 years, waveguide technology was the dominant method of transmitting electromagnetic energy.

However, by the end of the 1950s, the decimeter, centimeter and in part the millimeter wavelength ranges were already well-developed. Scientifically and technologically the ground was therefore prepared for development of components and systems in the near mm and sub-mm ranges. Thanks to the shorter wavelength, the QO principles: (1) keep the beams well collimated so that the edge illumination of limiting apertures, focusing elements, and scatterers is relatively low, and (2) follow geometrical optics and physical optics rules for directing and focusing the beams, quickly proved to be very fruitful in these wavelength ranges and opened wide opportunities for the design of necessary components and circuits. During these years a breakthrough was achieved in the working out of the QO techniques for transmission and processing of electromagnetic waves propagating in the form of Gaussian beams.

As mentioned above, the idea of transmission of electromagnetic power from a transmitting antenna to a receiving one by a directive wave beam was tested in the initial studies of “Hertz waves”. Therefore it was quite natural that these simplest free-space QO systems had been developed, studied and used in various applications before the appearance of other types of QO transmission lines.

15.4.1 Reflector and Lens Antennas

Despite low level of interest in microwaves during the 1920s and 1930s, scientists occasionally applied QO approaches when making antennas for communications with shorter waves. All of them were in fact one or another form of parabolic-dish antenna, whose principle of operation is clearly an optical one. The following are some highlights (from [53]):

- *1916.* Marconi and Franklin built a parabolic cylinder antenna for λ=15 m,
- *1922.* Marconi demonstrated a communication link, in New York, using two parabolic reflectors, λ =1 m,
- *1932.* Marconi experimented with an over-the-horizon communication system in the Mediterranean using a 50-cm diameter parabolic dish,
- *1934.* A. Clavier established the first wireless telephone link between France and the UK, λ =17 cm.

With the war steadily approaching, the new area of radar antenna design quickly developed:

- *1937.* G. Southworth reported on the focusing of centimeter waves [54],
- *1938.* A. Slutskin in the USSR designed the first 3-coordinate pulsed radar working at λ =60 cm with a 3-m ($D = 5\lambda$) dish reflector (Figure 15.14) [55].

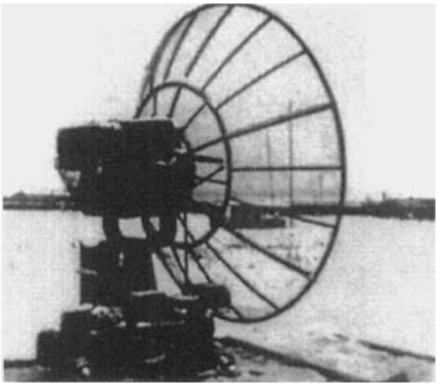


Figure 15.14. Dipole-fed 3-m diameter reflector antenna of the first Soviet 3-coordinate pulsed radar operating at a wavelength of $\lambda = 60$cm used in 1938.

It must be noted, however, that early reflector antennas were designed with the simplest GO principles, and did not allow for wave optics effects such as edge diffraction, spillover sidelobes, and backward radiation. The feeds were also simple: half-wavelength wire dipoles placed in the GO focus that failed to provide the reduction of the reflector edge illumination that is standard today. As mentioned in [55], a computation of the radiation from Slutskin's radar antenna using an accurate numerical method shows that its 5λ reflector was able to provide the far-field power pattern having an 18° by 24° main beam size and sidelobe levels of -7 and -10 dB in the E and H planes, respectively.

The further history of reflector antennas is well known and shows that significant improvement of their performance was achieved only when both theory and practice started using essentially QO ideas and methods. In the USSR, many laboratories were involved in R&D on microwave and mm-wave reflector antennas. One of the major non-defense application areas was satellite-TV and long distance communication. A network of ground stations known as the *Orbita* system was created by the end of the 1960s. They were equipped with 12-m parabolic reflectors working in C-band [56], and provided TV coverage for the most distant parts of the USSR.

Another very specific R&D area related to QO was the development of large reflector antennas for radio astronomy observations of cosmic sources of microwave and mm-wave radiation. This large-scale and interdisciplinary problem has been addressed in numerous publications. Therefore we here restrict ourselves to work from the USSR that was closely related to or based on the principles of quasioptics (QO). In 1956, the scientists of the P. Lebedev Physics Institute, Moscow (now LPI RAS) led by A. Salomonovich and P. Kalachev started designing the first radio telescope in the USSR, the RT-22, having a 22-m diameter parabolic dish antenna. It was built in Pushchino near Moscow in 1959 [57] and for a while was the largest instrument of this type in the world (Figure 15.15). The first study carried out was of radio emission from the Sun at $\lambda = 8$ mm, and also from Venus at $\lambda = 8$ mm and 4 mm. Subsequently, the experiments

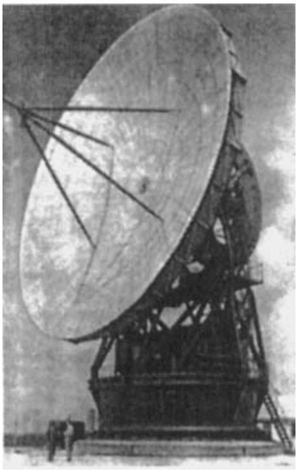


Figure 15.15. The radio telescope RT-22 used in 1959 with a 22-m diameter parabolic dish antenna in Pushchino near Moscow (reproduced from [57]).

using the RT-22 were greatly extended, especially after the telescope was equipped with more sensitive receivers [58, 59]. QO components of various types were used in the design of mm wavelength radiometers. The experience obtained with the first RT-22 in LPI RAS was later of great value when the Academy of Sciences decided to build a similar radio telescope on the coast of the Black Sea. In 1966, the second radio telescope RT-22 of the Crimean Astrophysical Observatory was built in Katsiveli, the Crimea, Ukraine [57], having a modernized antenna system. In particular, unique receivers using QO oversize waveguide components enabled radio astronomy investigations over a very broad range of frequencies including the sub-mm range. In the 1970s two even larger parabolic antennas were built — the 64-m TNA-1500 near Moscow and the 70-m RT-70 in Yevpatoriya, the Crimea [60], Ukraine. Here, one of the tools to achieve a record 0.74 efficiency was the use of a shaped subreflector [61]. In the 1988, a fixed 54-m radio telescope of the USSR Academy of Sciences, ROT-32/54, was built even further to the South, in Armenia. Similar to the famous Arecibo telescope, its primary reflector was a fixed section of a sphere. In the present case, the surface was composed of 3800 adjustable panels, and the beam could be pointed over a large range of angles by rotating the correcting secondary reflector, feed, and receiver, about the center of the sphere. The operating range of this instrument extended to $\lambda = 1$ mm, and QO components were widely used in the signal processing circuits [62].

Towards the end of the Soviet period, an absolutely unique 8-mm wavelength QO phased-array antenna was built near Moscow. Called *Ruza*, it was intended for space tracking and target recognition applications. It was assembled from as many as 144 separate antennas each a shaped as dual reflector system. Here, the feeding of radar from two 0.5 MW gyroklystrons was provided by the circular oversized waveguide (OSW) using the H_{11} mode. In the receiving circuit, free-space Gaussian-beam forming was applied [63]. Much of the above-mentioned work on QO antennas was led by or based on the theory developed by B. Kinber, who taught at the Moscow Physics and Technology Institute and worked at various research establishments, most notable of which is the R&D Institute "Radiofizika" of the USSR Ministry of Radio Industry (now a joint-stock company of the same name).

Lens antennas were suggested almost as early as reflectors. However, QO applications of classical homogeneous lens designs remained restricted to aperture phase correction in mm-wave horn feeds. At the same time, inhomogeneous lenses that were only theoretical curiosities at traditional optical wavelengths were realized in the microwave range and still attract much attention. These include the Luneburg lens, the Maxwell "fish-eye" lens, and others. The spherical or cylindrical Luneburg lens has a dielectric constant varying smoothly from 2 at its center to 1 at its outer boundary, which is the focal surface in the geometrical optics (GO) approximation. While lens dimensions are larger than microwave wavelengths, spheres with a dielectric constant varying smoothly on the scale of the wavelength are impossible to fabricate. Therefore various sorts of Luneburg lenses employing discrete dielectric layers have been devised. The oldest one consists of a finite number of spherical or cylindrical layers each with constant permittivity. Such lenses were investigated experimentally, e.g., in [64, 65]. In the USSR, dielectric lenses were developed by several organizations starting in the 1970s, as indicated in [66]; their applications were, however, restricted to defense. Today the Luneburg lens is an attractive candidate antenna for multibeam wideband mm wavelength indoor and outdoor communication systems [67], and for airborne surveillance radar applications.

It is necessary to note that reflector and lens antennas are normally fed with horn feeds. Here, an important engineering rule is that the feed should provide an illumination of the antenna edge at the level of −10 dB with respect to the central point. Then, the antenna performance in terms of directive gain is optimal. This empirical rule is approximately valid for any QO system, although for systems carrying out extensive manipulations of Gaussian beams a more conservative rule of −20 dB to −35 dB is common [19].

15.4.2 Circuits for Antenna Feeding and Gyrotron Coupling

The QO Gaussian beam approach was widely used in the development of the feeds for microwave relay stations and ground-based antennas for radio astronomy, as well as satellite and deep-space communication [68-70]. Power transfer by a narrow beam from a stationary receiving-transmitting unit to the main antenna eliminated the long coax or waveguide transmission line (and associated losses), and provided good performance over a wide frequency range. Here, the basic unit was a free-space transmission line formed by two reflector antennas whose beams were focused on each other (Figure 15.16a). QO feed systems often employed "periscopic" arrangements formed by various combinations of parabolic and flat reflectors (Figure 15.16b). Similar combined

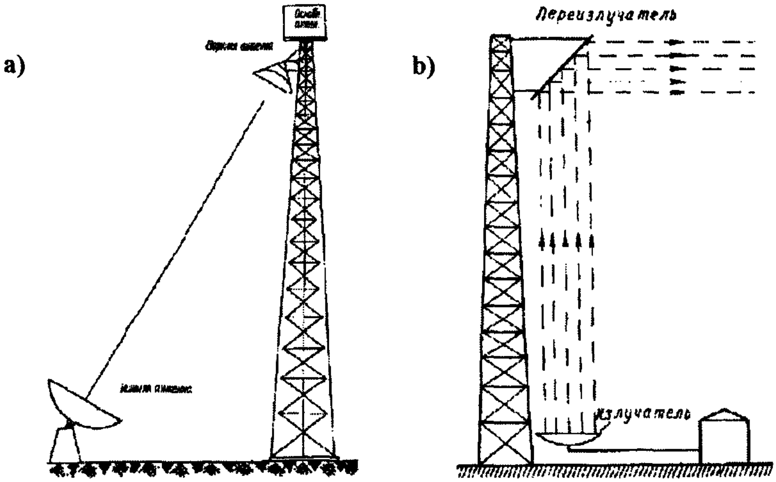


Figure 15.16. a) A microwave wireless power transmission line made of two focused reflector antennas, and **b)** a line of the periscopic type (reproduced from [68, 69]). Circa 1965.

reflectors were also used in laboratory antenna measuring ranges of the QO type [26].

In 1966, A. Gaponov of the R&D Institute of Radio Physics (RDIRP) in the Nizhny Novgorod State University, Russia proposed a new high-power source of microwaves and mm waves – the gyrotron [71]. Due to the specific geometry of this vacuum tube and the "whispering-gallery" field pattern of the operating mode, it was easier to deal with its output as a beam radiating into free space. Therefore a natural idea was to capture this beam and guide it with reflectors. Such a system was designed at RDIRP by V. Averbakh, S. Vlasov et al. [72,73]. This coupling system is able to provide efficient output by coupling up to 90% of power into the guided Gaussian beam. This design, often referred to as a Vlasov coupler, proved to be so successful that it is widely used in mm-wave systems based on gyrotron sources. Here, the most impressive application is definitely the heating of the plasma in controlled fusion machines with 110-170 GHz mm waves from 1-2 MW gyrotrons [74,75].

The principles considered above, i.e. beam focusing and −10 dB edge illumination, have been commonly used in the elements and devices of all two-aperture systems. Many of them have turned out to be applicable to other QO transmission lines. Nevertheless, it should be noted that the total length of the free-space Gaussian beam between the two apertures could not exceed the range of the Fresnel zone. This limited the area of applications of open-type QO systems and led to the emergence of periodic reflector beam waveguides (see section 15.6.2).

15.4.3 Components for Beam Manipulation

In the 1950s and 1960s, as a result of research into propagation between receiving and transmitting antennas with Gaussian beams, a number of specific QO devices were developed which were able to perform a variety of functions. A pair of prisms having a controlled small gap between their facets was an early idea of Bose [34]. Now it was used in the design of directional couplers, absorbing attenuators, SWR meters, polarization converters, etc. [8,10,76]. Another element, which found very wide application in QO technology, was a beam splitter based on a partially transparent dielectric plate tilted relative to the beam propagation direction. In particular, such an arrangement was used as a principal part of the design of a passive antenna duplexer [76].

An important stage in these developments came with the invention of various artificial dielectrics and periodic structures, as their specific properties enabled one to build a number of new QO devices and systems. The proposed artificial media can be subdivided to the structures consisting of scatterers and those of the waveguide type [8, 10]. In particular, a waveguide structure formed by a set of equidistant metallic plates was widely used in the design of polarizers, polarization-selective reflectors, polarization converters, etc. On the basis of a similar structure, a duplexer working with the circular polarization was made in the early 1960's by R. Fellers [76]. A laboratory device of this kind ($\lambda = 8.5$ mm) is shown in Figure 15.17.

Periodic structures of various types used as efficient polarization-sensitive elements have played an extremely important role in the development of QO techniques. Polarization discrimination is a property of dense grids (i.e., having small period, $p < \lambda/5$) made of highly-conducting wires or strips. Therefore, such a grid is rather a quasi-static device than a QO one. Experiments show that when a well-collimated beam is incident on finite-size periodic grid that has overall dimensions much larger than the beam size, its reflection and transmission characteristics can be predicted by using the theory of plane-wave

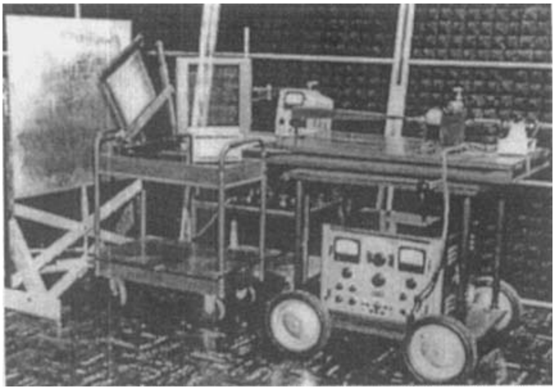


Figure 15.17. Open type antenna duplexer for operation in a circularly polarized mode at $\lambda = 8.5$ mm used in 1962 (reproduced from [76]).

scattering by an infinite grid. This greatly simplifies the design of grid polarizers. In the mid-1960s, on the initiative of the team of LPI RAS, led by academician A. Prokhorov (1916–2002; Nobel Prize winner 1964) (Figure 15.18) whose goal was developing mm-wave spectroscopy, the Central Design Bureau of Unique Instrument-Making of the USSR Academy of Sciences developed a technology for making tungsten-wire grids tightened on a metal-ring frame. Later such gratings were produced at the Moscow Electric-Bulb Plant having wide range of parameters: wire diameter $2b$ = 8 to 20 μm, periods p = 20 to 400 μm, and frame size $2a$ = 40 to 100 mm [77]. This enabled researchers of LPI RAS first to measure the properties of these grids [78] and then to design QO sub-mm wave Gaussian beam type measuring equipment [77], including a polarizer (Figure 15.19), Fabry-Perot interferometer, attenuator, polarization plane shifter, calibrated wavemeter, and others. The same grids were used in the first experimental polarizing devices in the sub-mm range based on hollow dielectric beam waveguide in the Institute of Radio-Physics and Electronics (now IRE NASU) in Kharkov (see section 15.6.1).

15.4.4 Measuring Systems for Spectroscopy and Plasma Diagnostics

Transmission of electromagnetic power between receiving and transmitting antennas by means of a directive beam was in use as early as the 1950s. It was utilized in laboratory measuring systems such as spectrometers and interferometers [79-83], their operation being implemented in an open type QO unit. At that time, together with designing devices for microwave bands [82, 83], similar systems were designed in the mm wave range [79-81]. A photo of the Michelson interferometer used for measuring the parameters of dielectrics in the 100 to 300 GHz frequency range [3] developed by F. Sobel in 1961 is shown in Figure 15.20.

Subsequently, similar devices found wide application as laboratory measuring systems. In particular, in 1967 a spectrometer based on QO circuitry was designed by N. Irisova *et al.* in LPI RAS for solid state research in the

Figure 15.18. Alexander M. Prokhorov, 1974.

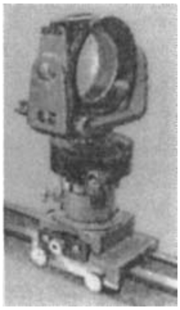


Figure 15.19. Millimeter-wave wire grid polarizer of 1968 (reproduced from [77]).

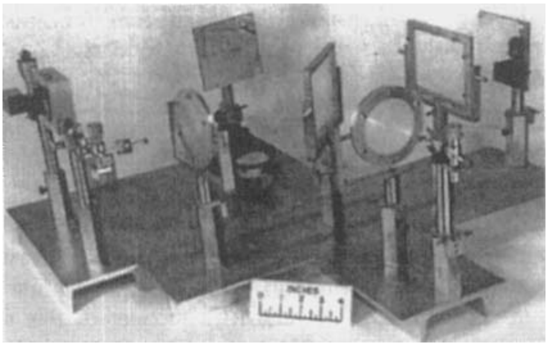


Figure 15.20. Open type Michelson interferometer used in 1961 for the study of dielectric characteristics in the frequency range f = 100–300 GHz (reproduced from [3]).

wavelength range of λ = 0.5 to 2.5 mm at liquid helium temperatures. Here, a paraxial plane-polarized wave beam was first collimated by a lens, guided by the set of reflectors, and eventually injected into a helium cryostat through a Teflon window [84]. The second lens, the material to be studied, and the InSb-based receiver were placed inside the Dewar flask. This system enabled analysis of absorption spectra of solid state samples cooled to helium temperatures with magnetic fields from 0 to 5 kO in the aforementioned wavelength range. In the USSR, this area of research was nicknamed as "BWT-spectroscopy" due to the use of backward-wave tube oscillators (BWT) as sources. These mm and sub-mm wave BWTs were developed in the R&D Institute "Istok" in Fryazino near Moscow (now "Istok" State Co) by M. Golant and his team [85]. The main characteristics of these sources were quite large output power (1-10 mW), continuous wideband tuning (50-100%), and one-to-one correspondence between the supply voltage and output frequency and power. Their working band reached 1200 GHz, and to cover the whole sub-mm wave range one needed 5 or 6 separate BWTs. In the 1970–1980s, the work on mm-wave spectroscopy employing open QO systems was greatly advanced by A. Volkov *et al.* in the Institute of General Physics of the USSR Academy of Sciences in Moscow (now IGP RAS) [86,87]. These researchers made wide use of additional focusing lenses when building complex sub-mm-wave interferometric circuits. This research was very much alike and in line with work carried out by their Western counterparts [88,89].

Besides spectroscopy, the second major application area of sub-mm waves until the 1990s was hot-plasma diagnostics. However, the development of corresponding technologies in this area followed different paths in the West and the USSR. Western plasma interferometers were based exclusively on open Gaussian-beam circuits, while *Tokamaks* in the USSR always used closed ones: first scaled standard waveguides then oversized metal-dielectric structures (see sections 15.6.1-15.6.3). This was because the *Tokamaks* built in the USA, Japan and Europe were constructed later than those in the USSR, and were designed from the start to accommodate large plasma cameras, and also because free-space components were well developed by that time. An example of successful application of the free-space (open) Gaussian-beam transmission line with periscopic circuitry was the 4-channel interferometer designed in the mid-1970s for the French experimental nuclear fusion machine *Tokamak-TFR*, with a HCN laser (λ=0.377 mm) as the source [90].

15.4.5 Long-distance Microwave Power Transmission

High-directivity narrow-beam antenna systems had been always attractive for microwave wireless power transmission (WPT). N. Tesla first suggested and tested this idea in 1899 [91]. In the USSR, a pioneer of this research was S. Tetelbaum (1910–1958) (Figure 15.21) at the Kiev Polytechnic Institute (now National Technical University "KPI"). In 1945 he considered the power efficiency of such a transmission line [92, 93]. He then became a head of the Laboratory of HF Currents at the Institute of Electrical Engineering of NASU (IEE NASU), whose staff worked during the period of 1948–1958 on several R&D projects related to WPT. The tasks of these projects encompassed the following: development of collimated beams and their focusing at given distances; determination of the efficiencies that could be obtained, taking account of atmospheric losses; development of microwave beams carrying CW power at the 10^3 to 10^4 kW level. To achieve these ambitious goals, Tetelbaum proposed and built in IEE NASU so-called "polyoscillators", in which the sources, integrated with in-phase radiators, were placed on a common surface [94]. Later he worked on the design of a city electric bus supplied with power from ground-based klystrons. However, the general level of vacuum electronics in the 1950s was not adequate for creating high-power systems. At the same time, the idea of "polyoscillators" can be considered as a prototype of the power combining arrays and phased antenna arrays which are now common in microwave technology. The projects performed in IEE NASU and KPI served as seeds for the development of sophisticated microwave sources in Kiev in the 1960–1990s. Here, it is important to note that the near-field gain of the aperture antennas implemented in microwave WPT was estimated with the aid of Physical Optics (PO) [95]. This analysis had shown, for example, that elliptical reflectors should be more efficient in this application than parabolic ones. It is interesting to find that in parallel to WPT with essentially Gaussian beams, a completely different idea had been actively pursued in the USSR until the early 1960s. This was long-distance microwave power transmission using a network of oversized circular waveguides [23] (see section 4.1). Many other researchers worked on microwave WPT [96, 97]. In 1968 P. Glazer in the USA realized that a potentially cheap and clean source of electric power could be an orbiting solar power satellite transmitting power to the Earth with a directive microwave beam [98]. In the USSR, theoretical feasibility investigations of this idea were also carried out in the 1980s [99]. Another fascinating proposal was connected with microwave-beam fed spacecraft. The originator of this idea was the Russian spacecraft and rocket pioneer K. Tsiolkovsky (1857–1935, Figure 15.22), who suggested it in 1924 [100]. His 80-year old paper is worth citing:

Figure 15.21.
Semion I. Tetelbaum, 1956.

Figure 15.22.
Konstantin E. Tsiolkovsky in the 1930's.

> *Finally, there is the most attractive way to acquire a velocity. It consists in the transmission of power to the shell from outside, from the Earth. The shell itself can avoid carrying a material power source, i.e. a weighted one, such as explosives or fuel. It will be transmitted as a parallel beam of electromagnetic rays of small wavelength. If its size does exceed several tens of centimeters, then such electromagnetic "light" can be directed as a parallel beam with the aid of a large concave parabolic mirror towards the flying airplane, and produce there the work needed for throwing away the particles of air or stored "dead" material, and for obtaining the space velocity already in the atmosphere.*

Forty years later a microwave WPT system was proposed to bring a spacecraft into orbit around the Moon [101]. The ground-based antenna was envisioned to be an array of 1000 parabolic elements ($\lambda = 3$ cm, diameter 10 m), and the on-board antenna, when unfurled, was to be a single parabolic one with a diameter of 100 meters (Figure 15.23). It was estimated that the latter could collect more than 30% of the radiated power at a distance up to 1000 kilometers. However, realization of these technically complicated global projects can be hardly expected in the near future. The solutions of more specific small-scale WPT problems seem to be readily accessible and are supported by a number of experiments. In 1964, a small helicopter powered by an electric motor was demonstrated. It maintained an altitude of 17 m during a flight lasting 10 hours, fed only by a microwave beam [102]. In 1975, a successful experiment was reported on microwave wireless power transmission of 30 kW power over a distance of one mile, on a ground test range [23]. In the 1990s microwave WPT technology was actively pursued at Kyoto University, Japan, where a phased array of printed radiating elements was used for forming the microwave beam. A detailed review of the research in this area can be found in [103].

These could be considered as the first successful demonstrations of microwave WPT if not for an amazing story that has been recently published in the Ukrainian newspaper *Zerkalo Nedeli*, no. 20 (445), 2003 [104]. In 1945,

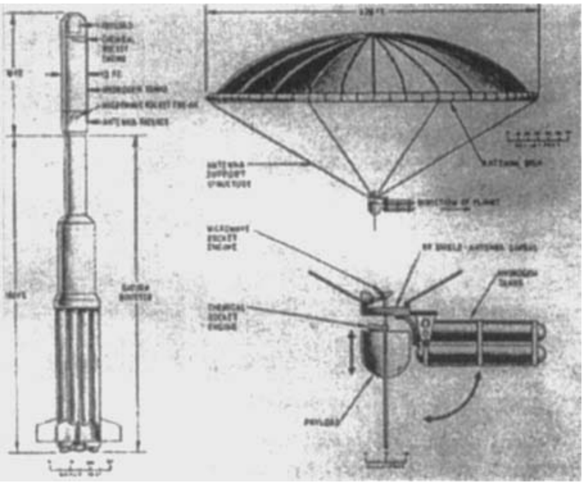


Figure 15.23. The design of parabolic antenna for the microwave engine designed to bring a spacecraft into orbit around the Moon (reproduced from [101]).

Soviet children at a summer resort *Artek* in the Crimea presented visiting American ambassador A. Harriman with a magnificent 1-m size wooden emblem of the American national bird. The feathers of the eagle had various colors due to the different sorts of wood employed. The emblem was placed on the wall in the ambassador's office in Moscow and during eight years survived four senior officials until it was found that a tiny microphone integrated with a small transmitter had been skillfully planted inside. It is hard today to imagine a realization of such project with components available in the mid-1940s, however the article insisted that the device was powered by microwaves beamed from a distant location, believed to be in a nearby building. Today this emblem is on display in the CIA "museum of spying" in Langley Virginia.

15.5 ALTERNATIVE: METALLIC OVERSIZED WAVEGUIDES (SINCE 1953) – QUASIOPTICS IN DISGUISE

In view of above-mentioned difficulties with free-space Gaussian-beam transmission lines, the interest of researchers was attracted in the early 1950s to metallic waveguides having cross-sections considerably larger than of the standard ones - so-called oversized waveguide (OSW). This means of transmission may have significantly lower attenuation than standard waveguides, but parasitic excitation and propagation of higher-order modes is possible and must somehow be handled. OSWs turned out to be quite promising and were used as basic building blocks for various systems and devices. In principle, one can study any closed waveguide by expanding the fields in terms of a modal series, and therefore we may say that OSWs are not essentially QO transmission lines. However, the duality between the modal and ray field representations was revealed by L. Felsen [105] and B. Katsenelenbaum [24] as early as in 1964. They demonstrated that summing up the modal series in multi-mode OSWs is asymptotically equivalent to using ray optics. For the analysis of long-distance propagation in regular OSW, ray optics is the superior approach for analysis and engineering, while diffraction from irregularities is more easily accounted for using modal expansions.

15.5.1 Circular Waveguide with the H_{01} Mode

The axially symmetric magnetic H_{01} mode in a circular metallic waveguide has an amazing property: as the cross-section is increased, its attenuation tends to zero considerably more rapidly than that of other modes. This is explained by the fact that the H_{01} mode does not excite longitudinal currents in the metallic walls, unlike all the other modes of hollow waveguides. In the 1950–1960s, this was the reason for increased interest in circular cross-section OSW with the H_{01} mode, as a promising multi-channel long-distance communication line. Large-scale research had been carried out on the physical properties of these waveguides, many functional devices had been developed, and experimental waveguide communication lines had been built. A review paper [106] summarized the results of a complex research project at Bell Telephone Laboratories. In the USSR this paper was published in a book [107], which collected a number of the key Western publications that comprehensively covered all aspects of the problem, including research at millimeter wavelengths. It concentrated on the examination of the H_{01} mode in circular waveguide, and on the experimental communication transmission line (length 125 m, diameter 120 mm). This line operated at a frequency of 9 GHz, i.e., with $S/\lambda^2 = 10.2$, where S is the cross sectional area of the waveguide. In the USSR, similar work started in the Institute of Radio-Engineering and Electronics of the USSR Academy of Sciences (now IRE RAS, Moscow) in 1953 (the year the institute was established), in the group led by Y. Kaznacheyev. The designers developed a waveguide transmission line in the wavelength range $\lambda = 5$ to 8 mm. Although this was a challenging problem, they had considerable success, developing all the necessary components for a circular H_{01} mode waveguide system: mode converters, matching transformers, angled bends, and directional couplers. They also developed measuring circuits, and studied the characteristics of components and the attenuation in the actual OSW. These results were published as a book in 1959 [108].

A number of problems concerning specific features of implementation of such waveguides with angled and smooth bends were highlighted in the later book of R. Vaganov, R. Matveev and V. Meriakri of IRE RAS [109]. Here a copper pipe waveguide of 60 m length was designed and constructed (Figure 15.24). Adjustment of the sections was carried out with the aid of precise optical instruments. In this OSW with inner diameter 60 mm ($S/\lambda^2=44.2$), the measured attenuation at $\lambda = 8$ mm was $2.5 \cdot 10^{-3}$ dB/m, compared with $1.85 \cdot 10^{-3}$ dB/m predicted by theory. The results of this project were released to the R&D Institute of the USSR Ministry of Communications in preparation for industrial

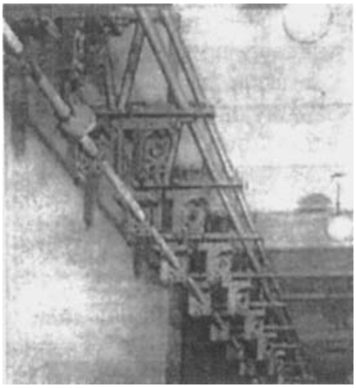


Figure 15.24. Experimental communication transmission line based on circular OSW using the H_{01} mode (f = 36 GHz) designed in 1957 at IRE RAS (reproduced from [108]).

production. The main intent was to provide a large (for the time) mm-wave bandwidth, typically from 50 to 100 GHz. However, in the early 1970s, research on circular OSW using the H_{01} mode as a communication line was terminated. The reason was the appearance of low-loss optical fibers, which solved the problem of long-distance communication on a new technological level. It should be noted that the operational principle of many devices used with a circular H_{01} mode waveguide system was the conversion of the latter into the H_{01} mode of rectangular waveguide, implementation of the required component(s), and then conversion back to the H_{01} mode of the circular OSW. In addition, the exciters of the H_{01} mode are large-size, complicated devices having appreciable loss. For these reasons circular H_{01} mode OSW failed to find wide application. The same fate awaited the proposal for long-distance microwave power transmission using the H_{01} mode in a network of large-diameter circular waveguides (1–2m in diameter) placed under ground [23].

15.5.2 Rectangular Waveguide with the H_{10} and H_{01} Modes

For rectangular cross-section H_{10} mode OSW, the common transmission line is a standard waveguide with more than tenfold increased cross-section relative to its single-mode counterpart [110]. In particular, using 3-cm range waveguide WG-16 (transverse dimensions 22.86 by 10.16 mm) at a wavelength of 2 mm (S/λ^2=57.5), one obtains an attenuation of 0.23 dB/m, or 20 times lower than with single-mode waveguide [111]. For 7.2 by 3.4 mm waveguide, the losses are as low as 1.4 dB/m in the wavelength range λ = 0.8 to 0.9 mm (S/λ^2=33.5) [112].

In the West, the properties of rectangular OSWs, including excitation difficulties, were examined in detail by the beginning of the 1960s [113]. Analysis of the linear smooth taper from a standard single-mode waveguide to the OSW [111,113] shows that, for efficient excitation of the principal mode in OSW, the taper length should provide, as a rule, a phase error, $\Delta\phi$, not greater than $\pi/8$ at the periphery of the taper aperture with respect to the phase at the aperture center. In the paper [114], the authors describe components in waveguide cross-section dimensions 7.2 mm by 3.6 mm for operation at a wavelength of $\lambda=1$ mm. They used a linear taper having a length of 152 mm that provided an error $\Delta\phi= \pi/12$. Using non-linear tapers and correcting the phase error with dielectric lenses and reflectors allows one to reduce the length of the taper by a significant factor [111,114]. When designing components for OSW, it is necessary to account for the possibility of propagation of higher-order modes. Thus, the application of waveguides of inhomogeneous cross section does not seem possible. In the paper [114], the use of OSW components in the wavelength range of λ = 0.5 to 8 mm built on the basis of a standard 3-cm band waveguide is described. These included pyramidal tapers, detectors, a cross-shaped divider based on a semi-transparent plate, a phase shifter, standard absorbing attenuators, and a Mach-Zehnder interferometer. Based on a waveguide of cross sectional dimensions 7.2 mm by 3.6 mm, a directional coupler (Figure 15.25), a tunable attenuator, and a phase shifter with a variable phase shift using a double-prism divider [114,115] were developed by J. Taub. Four section filters using stacks of fused-quartz plates were developed, having losses below 3 dB in the 130-145 GHz passband and attenuation greater than 20 dB in the 291-308 GHz stopband. Analogous components for wavelengths between 0.5 mm and 8 mm were presented in [116], including cross-section transformers, bends, phase shifters, attenuators, and also a λ = 0.65 mm Mach-Zehnder interferometer for plasma studies. The paper [111] considered a right-angle bend in rectangular OSW employing a plane reflector that was used in channel switch. Various combinations of faceted reflectors enabled the researchers to design phase shifters and balanced mixers [111,116].

In the USSR, rectangular OSWs were used as the basic transmission line in various millimeter and sub-millimeter systems developed in the RDIRP, and later in the Institute of Applied Physics of the USSR Academy of Sciences

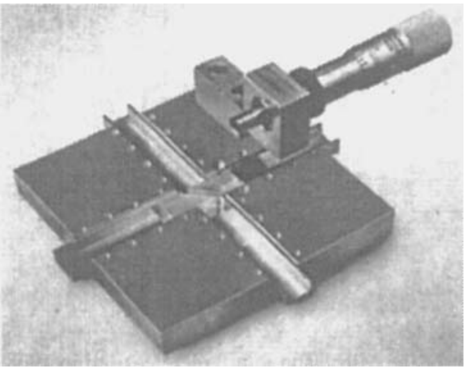


Figure 15.25. Directive coupler on the basis of rectangular OSW with the H_{10} mode having a cross-section of 7.2 by 3.6 mm for f= 345 GHz (reproduced from [114]).

(now IAP RAS) in Nizhny Novgorod. In their research on rectangular OSW, the scientists from Nizhny Novgorod used not only the H_{10} but also the H_{01} mode. Both modes led to identical design principles for functional elements, but employing the H_{01} mode enabled them to achieve slightly lower loss in the waveguide. In 1968 L. Lubyako built an interferometer based on rectangular OSW with cross-section 23 mm by 10mm for the wavelength range 1 mm to 4mm [117]. Figure 15.26 depicts its principal component, a cross junction with a reflector formed by a metallic cube, acting as a 50-50 power divider for each of the beams incident from two input arms. In subsequent work in Nizhny Novgorod, QO interferometric circuits were widely used in various systems. Lubyako developed an original method of studying dielectrics and ferrites with a Michelson interferometer based on the mentioned OSW [118]. L. Fedoseev suggested using a Mach-Zehnder interferometer in superheterodyne radiometers at $\lambda = 1.1$ mm – 1.6 mm (OSW cross-section 23 mm by 10 mm) and at $\lambda = 0.8$ mm – 1.1 mm (OSW cross-section 11 mm by 5.5 mm) [119]. Such a device provided operation with an intermediate frequency in the microwave range, in addition to including a coupler for local oscillator injection, which also suppressed parasitic signals and attenuated heterodyne noise [120]. In Figure 15.27, one can see the components (a) and superheterodyne radiometers (b) based on the rectangular OSW that were used in numerous systems developed in IAP RAS by Y. Lebsky, e.g., in the radio-astronomical investigations of the Moon, Venus, Jupiter, and galactic sources [121,122], and in the study of the atmospheric ozone layer [123].

15.5.3 Circular Waveguide with the H_{11} Mode

Circular OSW with the H_{11} mode has characteristics comparable to the rectangular OSW. It had also been used since the 1970s, in the realization of antenna feed systems in the mm-wave range [124]. Investigations have shown

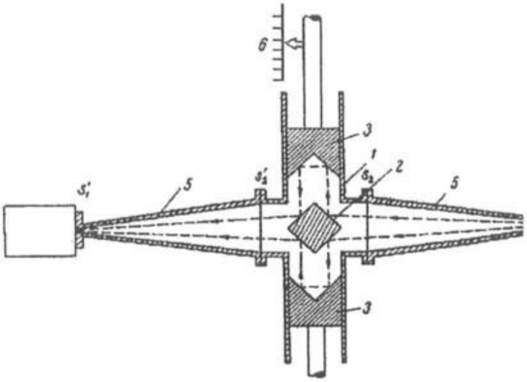


Figure 15.26. Circuit of the Michelson interferometer used in 1968 based on rectangular OSW with cross-section of 23 by 10 mm working with the H_{10} mode at $\lambda = 1$-4 mm designed at IAP RAS (reproduced from [117]).

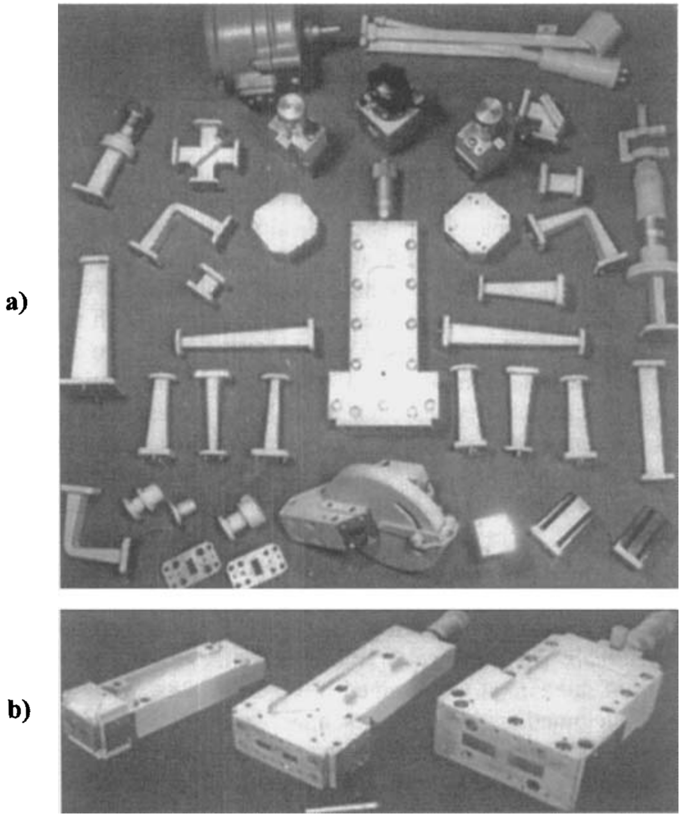


Figure 15.27. The components of 1970 **a)** and superheterodyne radiometers **b)** based on the rectangular OSW with the H_{10} mode developed at IAP RAS (photo provided by L. I. Fedoseyev).

that the losses in such a waveguide can be quite low. In particular, in the 3-mm wavelength range with waveguide diameter of 24 mm ($S/\lambda^2=50.3$), they do not exceed 0.1 dB/m [125]. For the excitation of these systems, one can apply both linear and nonlinear smooth tapers. Here, it is necessary to note that for non-axisymmetric modes in a circular waveguide, there is polarization degeneracy. As a result, a discontinuity (e.g., a section with small ellipticity), can produce transformation of the H_{11} mode into higher-order modes as well as excitation of the H_{11} mode with the orthogonal polarization. In the work [109], methods of minimizing H_{11} mode conversion in the circular OSW were considered. It was shown that together with reducing the deformation of the waveguide walls to a minimum, it is important to shorten the inhomogeneous section of the waveguide where the power coupling between the modes occurs. Therefore, application of similar systems in the case of extended lengths of waveguide section did not seem possible. At the same time, when the full length of the circuit containing all the elements meets the requirements formulated in [109], circular H_{11} mode OSW could be used in the design of various millimeter-wave systems.

In the 1970s and 1980s, these ideas were realized in the IRE NASU in Kharkov when building a number of antenna feed systems in the 2 mm wavelength range for pulsed and continuous-wave radar systems [126, 127]. Implementation of such QO systems became possible after V. Churilov, A. Goroshko and G. Khlopov proposed and studied, in 1970, an open-ended hollow dielectric beam-waveguide (HDB, see section 15.7.1) as an antenna feed [128, 129]. This development enabled them to avoid using standard waveguide components at the antenna front end. It also eliminated "locked-mode" resonances, and provided the desired amplitude and phase pattern across the antenna aperture [127]. A similar scheme was implemented when building antenna feed circuits on the basis of the circular waveguide with the H_{11} mode. Here, G. Khlopov and A. Kostenko used circular OSW of 20-mm diameter for a number of general-purpose components (power dividers, polarization converters, etc.) and some specialized devices such as reflector antenna feeds, scanners, rotating joints, and antenna switches. In particular, a ferrite antenna duplexer was designed and studied in the 2-mm wavelength range [130]. A specific feature was the application of impedance matching using multilayer ferrite structures [131, 132]. The matching of such a ferrite element made of two or more disks with controlled spacing, enabled one to eliminate reflections for two orthogonal components of the circularly polarized field that have different phase velocities in a longitudinally magnetized gyrotropic medium. This allowed the authors to achieve a remarkable performance of the receiving-transmitting system as a whole. A photo of this circuit is presented in Figure 15.28a, while general view of the system integrated with oscillators and placed behind a dual reflector antenna is shown in Figure 15.28b. Most of the components were designed as single compact units, which eliminated the waveguide flanges and shortened the total length of circuit, both extremely advantageous in the development of short wavelength systems. In the work [130], implementation of an optoelectronic antenna duplexer was considered. Here channel switching is under the control of a semiconductor laser, whose light pulse illuminates a semiconductor plate placed diagonally in the cross-section of the OSW cross-shaped junction.

It is important to keep in mind that all metallic OSWs have one intrinsic demerit - the lack of self-filtering of the higher-order modes – with the consequence that special design measures to suppress these modes are generally required.

15.6 COMPROMISE NO. 1: DISCRETE BEAM WAVEGUIDES AND EAST-WEST COMPETITION (SINCE 1961)

The limited distance of free-space Gaussian beam propagation between a pair of apertures can be overcome by arranging periodic or iterative correction of the phase distribution in the beam cross-section. Such an approach was considerably stimulated by the idea of using the Fabry-Perot interferometer as a laser cavity, suggested independently in 1958 by R. Dicke [133] and A. Prokhorov [134], and also by A. Shawlow and C. Townes [135]. Soon, a theory of resonators with spherical reflectors was developed, for which the natural oscillation modes were

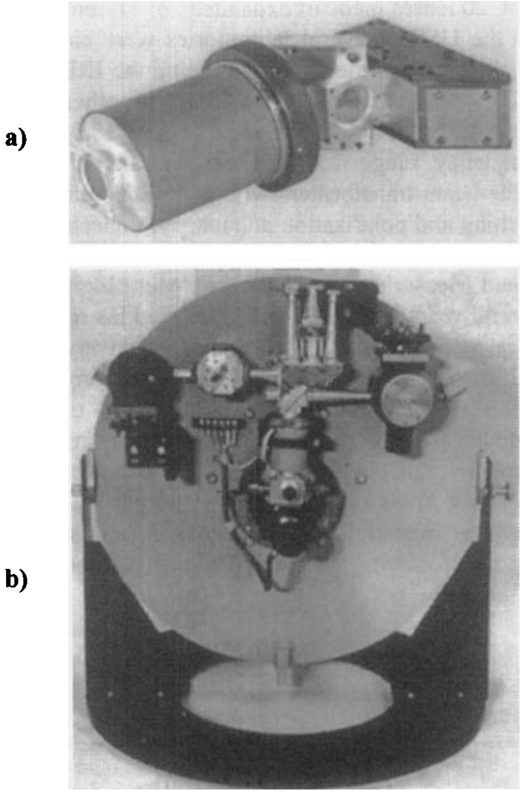


Figure 15.28. Single-antenna receiving-transmitting systems in the 2-mm wavelength range based on 20-mm diameter circular OSW with the H_{11} mode developed at IRE NASU in 1978: **a)** the single, compact receiving-transmitting unit with ferrite antenna duplexer; **b)** general view of the system on the rear of a dual-reflector antenna.

presented in the form of Gaussian wave beams [136-138]. An analogous modeling approach, in the Fourier-transform domain, was developed by G. Goubau and F. Schwering [139], who also proposed a beam transmission line formed by a system of equidistant lens-type phase correctors, and introduced the term "beam waveguide". The whole decade of the 1960s witnessed active competition between the Western and the USSR teams who were engaged in mm-wave reflector and lens type transmission line research. Here, researchers in the USSR enjoyed full access to the relevant Western publications while the opposite was not always possible. Broadly speaking, although theoretical results were relatively rapidly published in the open literature, measurements and practical designs frequently remained classified for a number of years.

15.6.1 Lens and Iris Beam Waveguides

The first experimental prototype of the lens beam waveguide [140] was designed by Goubau in 1961 for a wavelength of 1.25 cm and clearly demonstrated its potential. In this system, 20 lenses made of expanded polystyrene were spaced by 1m (Figure 15.29). In the USSR, several laboratories were engaged in similar research starting from 1962, one of the main ones being the IRE RAS, Moscow, with a team led by B. Katsenelenbaum (Figure 15.30). Another important team worked in Nizhny Novgorod led by V. Talanov (Figure 15.31). A lens beam waveguide in the frequency range 75 GHz, as well as a number of QO components: (waveguide-beam transformers with pyramidal and bimodal horns, mode converters, absorbing and polarization attenuators, dielectric beam divider, and reflection-coefficient gauge) were developed by A. Akhiyezer at the R&D Institute of Measures and Measuring Devices (now "Metrologiya" State Co.) in Kharkov, Ukraine. Several years later Akhiyezer collected his results in the book [141]. In the next several years this area of research was actively pursued both in the West and in the USSR. The lens beam waveguide was implemented when building QO measuring circuits for plasma diagnostics, materials science measurements, QO antenna-feeding systems for remote sensing and radar, and other important applications. An overview of the accomplishments of various Western teams can be found in the monograph [19]. In particular, Figure 15.32 shows a dual-wavelength receiver in plasma diagnostic system, and Figure 15.33 shows the transmitting and receiving circuits of a dual-frequency QO material measurement system.

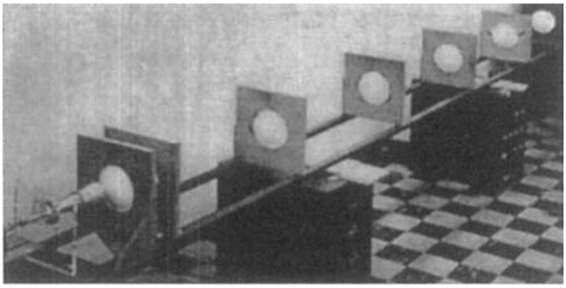
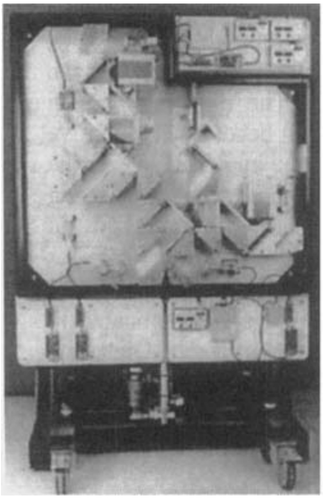


Figure 15.29. Goubau's experimental lens type beam waveguide of 1961 (reproduced from [140]).

Figure 15.30.
Boris Z. Katsenelenbaum in the 1960s.

Figure 15.31.
Vladimir I. Talanov in the early 2000s.



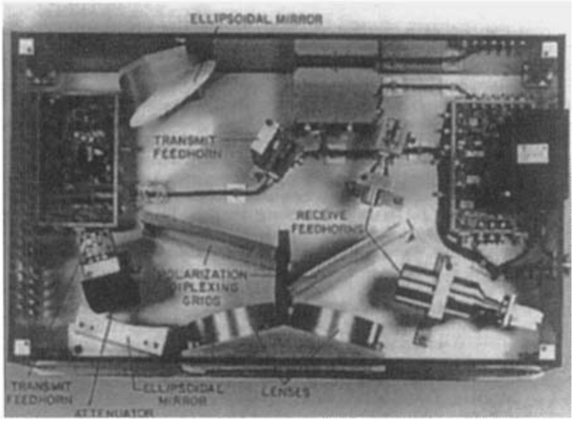


Figure 15.32. (top)_Dual-wavelength quasioptical receiving circuitry used in plasma diagnostics system (reproduced from [19]).

Figure 15.33. (bottom) The incident and reflected power channels of quasioptical material measurement system used in 1988 (reproduced from [19]).

The shortcomings of the lens beam waveguide are the power absorption in the dielectric and the reflection from the lens surface. Though the single-lens reflection losses are relatively small (e. g., 0.02 dB was reported in [140]), when building extended multilens circuits, this factor may spoil the overall characteristics. One of the possibilities to eliminate reflections is use of the lens guide proposed by V. Shevchenko at IRE RAS in 1963 [142]. Here, the lenses were elliptic paraboloids inclined relative to the beam axis by Brewster's angle. This provided the phase correction equivalent to that of a conventional lens [143]. An experimental model of such a beam waveguide was built at IRE RAS in Moscow and tested in the sub-mm range (λ = 0.9 mm – 0.7 mm) [144]. The waveguide consisted of 22 polyethylene lenses of maximum thickness 3.2 mm, separated from each other by 10 cm distance. This beam waveguide provided losses no greater than 1.7 dB/m. Beam waveguides employing non-reflecting lenses were used later when designing measurement setups and developing spectroscopic techniques for the study of various materials including low-loss dielectrics, ferrites, semiconductors, and liquids, [27,145]. This work was also performed at IRE RAS and was led by Meriakri.

A diaphragm or iris beam waveguide is closely related to the lens one - its focusing effect depends on truncation of the beam, although it does not entail any explicit phase correction. This transmission line was also the subject of competition between Western and Soviet researchers. In [146], a beam waveguide having rectangular diaphragms was considered by Goubau for use in the wavelength range λ = 4 mm to 8 mm. In [144], results actually related to the work started in IRE RAS in 1964 were published, describing the studies of a beam waveguide, using metallic iris apertures to provide a smooth control of the aperture size (λ = 0.7 mm – 0.9 mm). In this system, the distance between the diaphragms was 12 cm, and the loss was 2.2 dB/m. The diaphragm beam waveguide has greater loss than does the lens waveguide. It becomes competitive only in the wavelength range shorter than 0.5 mm due to the increased loss in the lens material [27]. The loss due to absorption in the lens can be reduced by using novel, low-loss materials. For example, Teflon F-4 not exposed to thermoprocessing has a loss tangent $\mathrm{tg}\delta = 0.25 \cdot 10^{-3}$ at λ = 0.6 mm while for standard Teflon the value is $0.7 \cdot 10^{-3}$. Dielectric reflection losses can be reduced by using artificial matching layers with grooves, but these are complicated to make, somewhat narrowband, and imperfect in their performance. Dielectric losses can be completely eliminated only by using a reflector analog of the lens beam waveguide.

15.6.2 Reflector Beam Waveguide

The reflector beam waveguide was patented in 1962 and published the following year by Katsenelenbaum of the IRE RAS [147]. Here, the reflector playing the role of a phase corrector was shaped as a section of the surface of an ellipsoid of rotation, although simpler shapes are acceptable (for instance, spherical reflectors [25]). The amplitude distribution in the transverse cross-section of the beam obtained in such a manner evidently has a more complicated structure than in the case of the axially symmetric lens-type beam waveguide. This is an important point to be kept in mind by the system designer. Practically at the same time, J. Degenford designed and measured a reflector beam waveguide in the 4-mm wavelength range using elliptic reflectors; the loss per single iteration being 0.015dB [148]. Another team in the USSR worked on reflector beam waveguides in the RDIRP in Nizny Novgorod. Paper [72] contained experimental data on such a device made of 8 reflectors shaped as rotationally symmetric ellipsoids. The total loss for this system was found to be 3.2 dB, including the loss due to the feed horns. The shortcomings of this transmission line were its quite large dimensions and very high sensitivity to the reflector adjustment. Therefore, the periscopic beam waveguide, in which reflectors are combined in pairs as fixed units, is preferable (Figure 15.34) [149]. If the spacing between the reflectors in

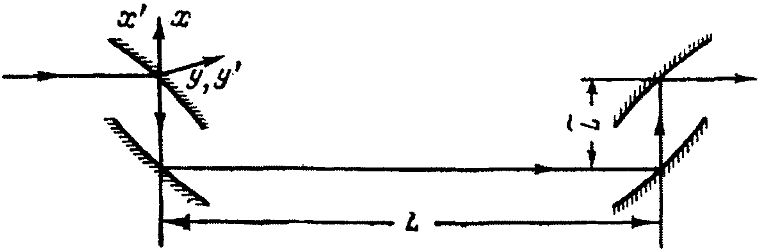


Figure 15.34. Periscopic reflector beam waveguide of 1965 (reproduced from [149]).

each pair is significantly smaller than their focal distance, than the phase correction of such a unit equals the sum of the two reflector corrections. Rotation of the device made of a pair of fixed reflectors yields a displacement of the beam parallel to its axis but does not produce a change in its direction. Hence the system as a whole is less sensitive to the misalignment of the phase correctors. An experimental test of such a line was performed in the optical range ($\lambda = 0.63$ μm) [150] and showed good potential. Although the marked technical shortcomings are still an obstacle to the wider application of reflector beam waveguides in the mm and sub-mm range, there are a few impressive implementations. One of them is used in the feed system of the dual-reflector scanning antenna of a deep-space satellite communication ground station (Figure 15.35) [70,151,152]. Here, a beam waveguide provides multi-frequency operation. Another important application is the transmission of mm waves in the 110-170 GHz range from high-power gyrotrons for nuclear fusion machines – tokamaks and stellarators [75], to provide electron cyclotron resonance heating of the plasma.

15.7 COMPROMISE NO. 2: CONTINUOUS BEAM WAVEGUIDES AS A WIDELY-USED USSR TECHNOLOGY (SINCE 1963)

In the design of certain measurement facilities, such as interferometers for hot plasma diagnostics in fusion machines or defense radar systems, the basic transmission line must have specific electromagnetic characteristics that are not provided by periodic beam waveguides. These include invariance of the field amplitude and phase along the guide, amplitude and phase symmetry in two orthogonal planes, linear polarization of the field, self-filtering of the higher modes, high degree of shielding, wide range of the working frequency, and low loss for the principal mode [28]. In addition, such transmission lines must satisfy a number of environmental requirements including mechanical rigidity and weather resistance. This relates to the transmission line, which is simultaneously a screen, a support structure for the functional elements, and a protection against external influences. All of these requirements are met by the "hollow dielectric channel" waveguide technology. This technology is based on circular or rectangular OSW, with inner walls completely or in part covered with a lossy dielectric or layered-dielectric lining (Figure 15.36). In spite of the difference in lining structures, these systems exhibit some common properties produced by the presence of the dielectric boundary of the channel, that justifies uniting them into a common class. In brief, the principal mode here has a field distribution which is nearly that of a Gaussian beam in cross-section, while the higher-order modes are filtered due to the increased absorption which they suffer.

15.7.1 Hollow Dielectric Beam Waveguide

This specific QO transmission line was conceived in 1963 by Y. Kuleshov (Figure 15.37) at IRE NASU in Kharkov. Earlier, his team had accumulated rich experience in developing standard waveguide measuring devices in the whole

Figure 15.35. Beam waveguide feed system of the dual-reflector antenna of a ground-based satellite communication station (reproduced from [151], Circa 1961).

Figure 15.37.
Yevgeniy M. Kuleshov, in 1960.

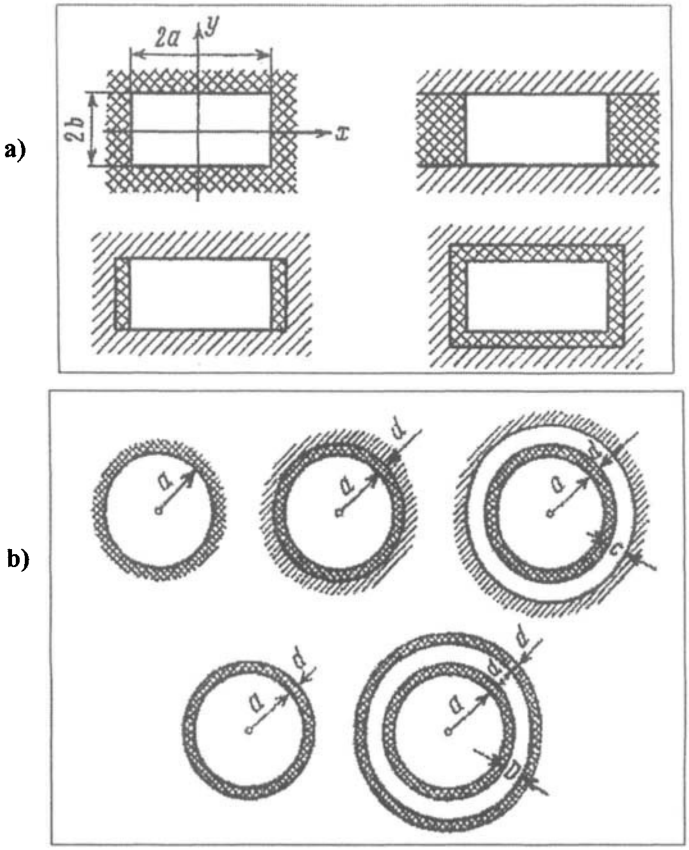


Figure 15.36. Waveguides of "the hollow dielectric channel" type with **a)** rectangular and **b)** circular cross sections (reproduced from [172, 175], Circa 1972).

mm-wave range – a series of projects had been performed with physically small single mode waveguides in the wavelength range between 1.5 and 8 mm. The requirements mentioned in the introduction to this section appeared quite natural for Kuleshov due to his involvement in the *Tokamak* plasma research underway at the Institute of Atomic Energy (now Federal Scientific Center "IAE") in Moscow. *Tokamaks* were extremely high-power devices, which worked in a pulsed mode and experienced very intense vibrations. Therefore a workable design for a mm-wave interferometer for precise measurements of the electron density of the hot plasma in these fusion machines had to provide rigid coupling between the sections of transmission lines and the measuring units. At first, Kuleshov had no idea of using hollow dielectric "beamguide" (or beam waveguide but called HDB) in *Tokamaks*; in fact the plasma density in the first fusion machines of this type was not very high (see section 6.3) and hence plasma diagnostics could be done with mm waves. *Tokamaks* requiring sub-mm wave interferometers came only after 1971, and then HDB was quickly selected as a basic technology.

The patent for HDB ("authors certificate" in USSR terminology) was entitled, "Dielectric beam waveguide of the sub-mm wavelength range". It was submitted, registered as classified, and declassified in 1969, 1971, and 1972, respectively, when the circuits based on HDB had already been in use for several years. The subject of the invention was formulated as follows [153]:

> *# 1. Dielectric waveguide of the sub-mm wave range, having the form of dielectric tube, whose distinction is that, in order to provide the necessary rigidity of the structure and avoid radiation, it is made of dielectric having the permittivity of 2.5 to 4 and loss tangent of 0.05 to 0.1 (e.g., phenoplastic), and fixed inside a flanged metal tube.*
>
> *# 2. In order to improve the filtering of spurious modes, the inner surface of the dielectric tube (see beamguide from # 1) is provided with longitudinal triangular ribs having depth smaller than a half-wavelength.*

It should be noted that a study of very great importance for HDB was published in 1964 by E. Marcatili and R. Schmeltzer [154]. They considered in greater detail the structure formally solved by J. Stratton in [155], i.e., a circular cylindrical channel in an unbounded dielectric medium, and found out that it could support quasi-single-mode propagation. Independently and half-a-year earlier, guided by engineering intuition and simple calculations, Kuleshov had selected a similar channel when designing a new basic transmission line for a set of broadband mm and sub-mm wave measurement circuits.

Although at first HDB had no clear area of application, this research was readily funded by the USSR Ministry of Radio Industry as an innovation potentially applicable to various systems. In 1964–1966 and 1968–1971, Kuleshov and his team developed and studied both HDB and a complete measurement setup covering the near-mm and sub-mm wave wavelength ranges. The first project was aimed at exploring the feasibility of developing a "kit" of HDB-based measuring devices in the wavelength range 0.7 to 1.7 mm. The HDB was fabricated as a Phenol plastic tube, the inner diameter being 20 mm or 40 mm, the thickness being 5 mm, which was placed inside a metallic tube with coupling flanges. Two variants of the beam waveguide had been developed: one with smooth inner surface and another with longitudinal ribs of triangular cross-section (Figure 15.38). The use of a relatively thick layer of Phenol, which had considerable loss, allowed elimination of the effect of the metallic tube, whereas the use of a ribbed surface lowered the effective permittivity ε_{eff} down to the value of approximately 1.5 that helped suppress the higher-order modes. The low-loss principal mode of HDB is the almost linearly polarized HE_{11} mode, whose phase front is almost flat in the waveguide cross-section, and whose amplitude pattern is very close to a Gaussian beam [156,157].

Experimental investigation of HDB was carried out in the wavelength range of 0.8 to 1.6 mm, and it was found that at sub-mm wavelengths ($\lambda < 1$ mm) the loss did not exceed 1 dB/m. Within the first project, a large number of innovative QO components based on HDB were developed, including waveguide-to-beam waveguide transitions, rotating joints, beam splitters with a semi-transparent dielectric plate, corner reflectors, transmission and reflection-type wavemeters based on Fabry-Perot open resonators, absorbing attenuators, phase shifters, thermistor mounts, absorbing loads, movable loads, movable reflectors. Despite the fact that most of the QO principles used here were known since the time of the "Hertz wave" pioneers, adapting them to the specific structure of HDB required considerable creativity and non-trivial technical solutions. Here, Kuleshov and Yanovsky were most frequently the authors of new ideas and configurations.

In view of an absence of immediate customers, the same USSR ministry funded Kuleshov's next project on HDB components only in 1968–1971. Its idea was to dwell on and refine the polarization principles in the measuring circuits for the wavelength range between 0.5 and 0.8 mm [158]. Working on polarization-selective QO devices, researchers showed that HDB of 20-mm diameter could be used over this whole wavelength range. Among new components were the following: double-lens transformers, Fabry-Perot wavemeter with metal-strips (1-μm thick silver or aluminum), grating reflectors made by vacuum deposition on the quartz substrate, phase shifters with dihedral

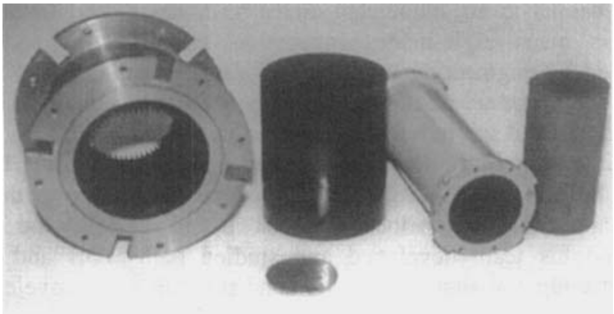


Figure 15.38. HDB sections of inner diameters 40 mm and 20 mm, with smooth and ribbed inner surfaces were developed in 1968 (photo provided by V. Kiseliov).

reflectors in the 90° angled bends of the beam waveguide. However, the main focus was on devices using gratings of 10-μm diameter tungsten wire, with periodicity between 20 and 60 μm, wound on 40-mm diameter frames.

By the middle of the 1970s, a complete set of HDB-based QO components had been designed, fabricated, and refined. It included waveguide to beam waveguide transitions, matched and movable terminations, reflectors, polarizers, transitions with controlled and fixed bending angles, telescopic and rotary junctions, wave meters, polarization attenuators, phase and frequency shifters, dielectric-plate and wire-grating beam splitters, reflectance gauges, matching transformers, amplitude modulators, electromechanical switches for the beam propagation direction, balanced mixers, duplexers, polarization transformers, and power meters (Figure 15.39) [28,159]. Together with general-purpose devices, specialized ferrite and semiconductor devices had been developed [160]. This *LEGO*-style kit of over 20 components and devices was later widely used in application research and new technologies. The kits were produced serially until the mid-1980s and purchased by more than fifty Soviet organizations that worked with mm and sub-mm waves. In all, over 6500 components and devices were produced. For example, a team led by Y.

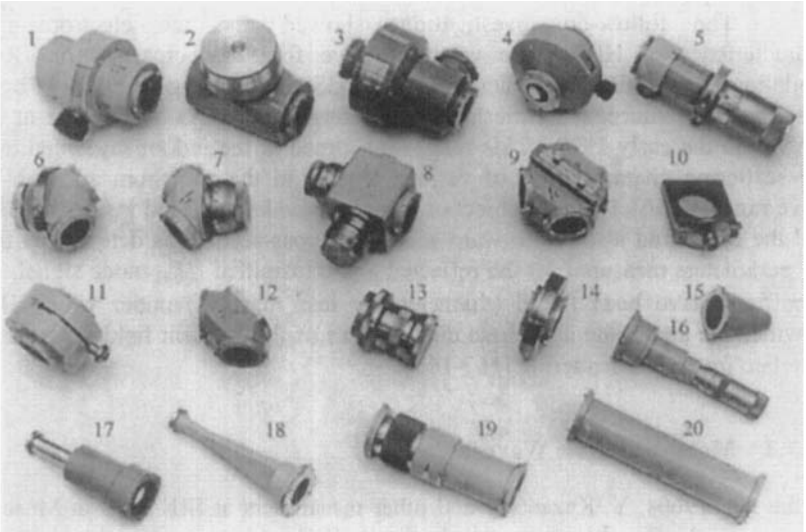


Figure 15.39. Quasi-optical LEGO-like kit for a sub-mm wave engineer. HDB-based components used for building wideband ($\lambda = 0.5$-1.7 mm) measuring circuits developed in IRE NASU: 1- polarization attenuator, 2- polarization phase shifter, 3- tunable attenuator-power divider, 4- polarization plane rotator, 5- wave meter, 6- polarization converter, 7- tunable phase shifter, 8- matching tuner, 9- beam splitter, 10- cassette of polarization discriminator, 11- linear polarizer, 12- right-angled corner, 13- movable two-facet reflector, 14- rotating joint, 15- terminating load, 16- movable reflector, 17,18- two waveguide-to-beamguide transitions, 19- telescopic section, 20- HDB straight section (photo provided by V. Kiseliov, 1971).

Gershenzon of the Radiophysics Laboratory at the Moscow State Pedagogic University, jointly with Kuleshov's team of IRE NASU, developed measuring circuits for sub-mm wave spectroscopy of semiconductors and superconductors [161,162].

Successful development of HDB-based components and instruments stimulated their use in antenna feed systems short-mm wavelengths. As a result, several teams at IRE NASU built multi-functional transmit-receive systems for prototypes of 2-mm wave radars. These prototypes were used in large-scale experimental studies of the performance of such radars in field conditions with various types of terrain and vegetation. In 1971, Kuleshov, Yanovsky and their colleagues of the IRE NASU proposed a duplexing device [163] that coupled both the transmitter and the receiver to a single common antenna for circularly polarized signals. This principle was well known in standard waveguide technology and in QO antennas [76,164,165]. The designers developed a novel version of the device, in which the polarization transformer was a combination of a wire grid and an adjustable flat reflector placed into a 90° bend of HDB. This duplexer was used as a principal unit for the HDB and MDW-based antenna feed systems designed in the 1980s at IRE NASU for 2-mm wavelength battlefield radars using a single antenna and circular polarization of transmitted/reflected signal [130].

The follow-on investigations showed that the electromagnetic characteristics of HDB were very attractive for radar cross-section (RCS) modeling. An HDB-based microcompact RCS testing range was built by V. Kiseliov, who succeeded Kuleshov as the head of the QO department at IRE NASU, in the early 1990s. This range was aimed at the indoor investigation of the scattering characteristics of various objects in the short-mm and sub-mm wave ranges [166]. Here, an object or its scaled model is placed inside the HDB, and the RCS (and also the forward scattering cross-section) is determined from the parameters measured for the reflected and transmitted HE_{11} mode signal. The conditions have been found (diameter not less than 5λ) under which HDB provides the amplitude and phase distributions of the incident field necessary to simulate free space scattering [167-169].

15.7.2 Metal-dielectric Waveguides

In the late 1960s, Y. Kazantsev and other researchers at IRE RAS in Moscow, who had at that time no idea of Kuleshov's HDB at that time, proposed another OSW technology with a metal-dielectric inner coating [170]. A detailed theoretical investigation of the basic idea can be found in [171]. A metal-dielectric waveguide (MDW) is commonly a large diameter ($\sim 10\lambda$) metal tube of rectangular or circular cross-section. The inner surface of the tube is covered with a low-loss dielectric layer, thus having the features of an impedance boundary. Unlike HDB, the thickness of the lining layer here is small, and can cover only a part of the inner metallic surface. The principle of operation is based on the fact that if the partial plane waves encounter the waveguide wall at grazing incidence (this occurs for the lower-order modes), the ohmic losses in the metal are significantly smaller than for all-metal OSW. The higher-order mode losses in MDW are greater than in OSW – this effect is referred to as self-filtering of the modes.

In circular MDW, the working mode is the lowest hybrid mode HE_{11}, the same as in HDB. In 1970, Kazantsev demonstrated that a remarkably low attenuation could be achieved [171]; this effect was analyzed in detail in [172]. In particular, the losses in MDW having a diameter of 40 mm were estimated to be $3.7\cdot10^{-3}$ dB/m at $\lambda = 2$ mm ($S/\lambda^2=314.2$) with a dielectric coating thickness of 0.25 mm and complex dielectric permittivity characterized by $\varepsilon = 2.3$ and $\mathrm{tg}\delta = 2\cdot10^{-4}$. In addition to the loss, Kazantsev considered MDW excitation problems, putting the design of MDW-based components on more solid ground than the theory available for HDB. MDW was quickly gaining a reputation of convenient and attractive low-loss sub-mm wave transmission line. Therefore, as an alternative to their own HDB-based designs, the same IRE NASU team of Kuleshov developed, in the early 1980s, a kit of QO components and instruments based on circular MDW having a diameter of 20 mm, whose inner surface was coated with a 0.2-mm thick Teflon layer. This waveguide enabled the designers to use a maximum of the already existing HDB technology without costly modifications. In particular, in [173] a QO circuit for a superheterodyne receiver was considered that used an intermediate frequency of 0.3 GHz, and operated in the wavelength range of 1.3 to 2.2 mm. The circuit included halfwave and quarterwave polarization interferometers, a wavemeter, a polarization attenuator, and was packaged in a very compact configuration. Similar integrated units were designed to serve as antenna feeds and for the mixers in the high-temperature plasma diagnostics facilities.

Rectangular cross-section MDW was also developed. It was designed having two options: one with the dielectric coating on two opposite walls, and the other with the coating on all four walls. The second case had the advantage of providing low-loss transmission of waves of two orthogonal polarizations, and was used in circuits implementing polarization conversion. In such a waveguide, the working mode is the longitudinal-magnetic mode LM_{11}. It is characterized by a practically flat phase front, linear polarization, and amplitude pattern having a maximum at the waveguide axis, smoothly decreasing towards its walls, and being symmetrical in the two orthogonal planes [174,175]. Experimental examination of the losses in MDW of rectangular cross-section was carried out at wavelengths between 8 mm and 2 mm. In particular, in the 2-mm range, the waveguide tested had a cross-section of dimensions 10 mm by 23 mm ($S/\lambda^2 = 57.5$), with 0.55 mm thick polyethylene layers ($\varepsilon = 2.3$, $\mathrm{tg}\delta = 5\cdot10^{-4}$) placed on the narrower walls. The measured loss was $3.0\cdot10^{-2}$ dB/m. Based on such a waveguide, various components and devices were designed in the 1970s at IRE RAS, Moscow by Kazantsev and his team members O. Kharlashkin and M. Aivazyan. These included exciters, waveguide bends, higher-mode filters, rotary junctions, and ferrite devices [175,176]. They were used in the development of antenna feed circuits in the 2-mm wavelength range. In the late 1980s, development of systems based on rectangular MDW was continued at the Institute of Radio Physics and Electronics of the Armenian AS in Yerevan (now

IRE AAS) [177], by R. Avakyan, K. Agababyan, and Aivazyan, who worked there by that time. They developed detector sections, mixers, and an integrated receiver for a radiometer [178].

At the same time at IRE NASU, Kuleshov developed a complete set of QO components for building measurement circuits in the near-mm and sub-mm wavelength ranges, based on square section MDW. Here, the square waveguides of two wall dimensions were used: 14 mm in the range λ = 1.15 to 3 mm, and 10 mm for λ = 0.7 to 1.7 mm [179]. The set consisted of waveguide sections, exciters, angle-bend transitions, a rotating junction, nonreflecting loads, a linear polarizer, a polarization transformer, a polarization attenuator, a phase shifter, a resonant frequency meter, dielectric and polarization power dividers, a movable reflector, a two-sided angled reflector, an amplitude modulator, and a ferrite isolator. In 1994, a square MDW of 14 mm by 14 mm cross-section was used when developing a single-antenna radar in the 2-mm range employing a circularly polarized signal (Figure 15.40) [180]. This work was accomplished by the joint efforts of the IRE team and a team headed by Churilov, of the Institute of Radio Astronomy (IRA NASU), which spun off from IRE in 1985.

15.7.3 High Temperature Plasma Diagnostics in the Moscow Tokamaks

The high mechanical stability of HDB-based circuits together with their excellent electromagnetic characteristics enabled the IRE NASU team to develop beam waveguide multichannel interferometers for the measurement of the electron density in the high temperature *Tokamak* controlled plasma fusion machines. In particular, in Figure 15.41, one can see a parallel array of HDB-based arms of the 9-channel interferometer (λ = 0.9 mm) mounted on top of the *Tokamak* T-10 of the IAE in Moscow [181].

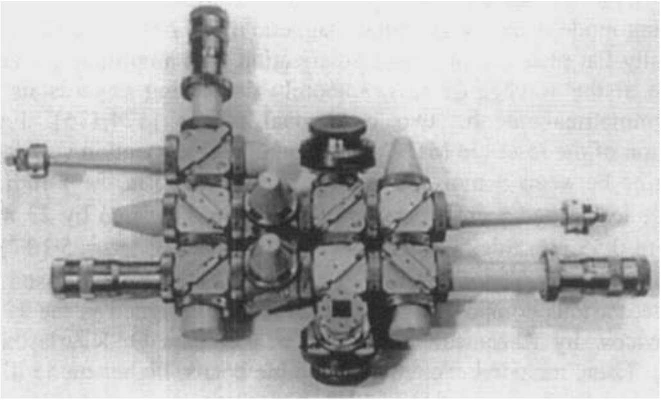


Figure 15.40. Single-antenna receiving-transmitting system employing a circularly polarized signal in the 2-mm wavelength range based on square MDW having cross-section of 14 by 14 mm developed at IRE NASU and IRA NASU (photo provided by V. Kiseliov, 1975).

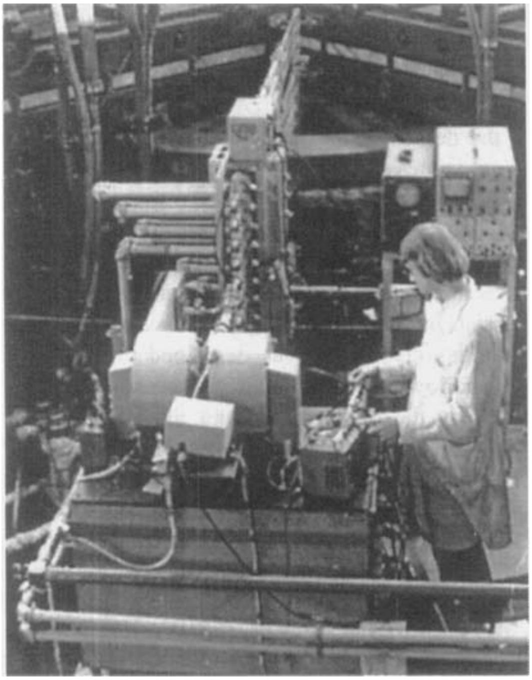


Figure 15.41 The first QO nine-channel HDB-based interferometer (λ=0.9 mm) with a BWT source for hot plasma diagnostics of the Tokamak T-10 at IAE (photo provided by V. Kiseliov, 1975).

In fact, the diagnostics of the high temperature plasma in *Tokamaks* was the best funded, although almost "invisible", area of application of QO sub-mm wave circuitry and measurement techniques in the USSR between 1973 and 1993. It is necessary to keep in mind that the Tokamak principle of creating very hot and dense plasma in toroidal camera was proposed in the USSR in the early 1950s. All related work was concentrated at the IAE, which was a huge laboratory of the State Committee for Atomic Energy (SCAE) in Moscow, and heavily classified. Today it is unbelievable that the location of the IAE was selected to lie within the boundaries of a large city, only 20 km from the Kremlin. This was the personal choice of Beriya, Stalin's powerful security minister and skillful manager, who supervised the nuclear industry. It was clear from the beginning that realistic power-generating machines of this type had to have cameras of large diameter, around 1 m, because a dense plasma can "live" long enough only if it is concentrated far from the enclosure walls. When the first small-size machines were built and thoroughly studied, it was revealed that one needed continuous control of the plasma density and internal structure. The required monitoring could be realized with electromagnetic waves but the denser the plasma the shorter the wavelength that is required to penetrate the plasma, determine the phase shift and thus the electron column density in the beam. In the first *Tokamaks*, sensing with radiation of 4 mm wavelength and later 2 mm wavelength was adequate. To build the required measurement circuits, IAE scientists led by N. Yavlinsky and then Y. Gorbunov used standard-waveguide components and devices developed in the IRE NASU in Kharkov and worked together with Kuleshov and his team.

In 1968, the design of the larger machine T-10 was conceived, and in 1970 the government approved it. The plasma density in it was expected to reach 10^{14} electron/cm^3, hence it was estimated that the sensing should be carried out at a wavelength $\lambda = 1.5$ mm or shorter. IAE scientists remembered that Kuleshov at IRE NASU already had components based on the standard waveguide 1.1 mm by 0.55 mm in cross-section available. When asked about the new project, Kuleshov gladly agreed to assist, but said that his approach would be based on a different (not waveguide) technology. In fact, as described in section 6.1, he had been already working on hollow dielectric beam waveguide (HDB). Thus, in 1973, a project was initiated by the IAE on studying the feasibility of a nine channel interferometer in the wavelength range 0.5 mm to 1.7 mm [182].

Scientists working with the Tokamak highly appreciated the new instrument, which was not sensitive to the intense vibrations characteristic of their pulsed fusion machine, and thus enabled them to avoid errors in the phase measurements. This was a result of the fixed length of the beam waveguides and the possibility of mounting them directly on the plasma camera supports. T-10 was operated for the first time in June 1975, and in December of the same year the nine channel QO interferometer was commissioned and made its first measurements at $\lambda = 0.9$ mm, fed from a BWO (backward wave oscillator) source (Figure 15.41). Associated HDB-based circuitry reached dozens of meters in length. The follow-up stages of plasma diagnostics research were directed toward further shortening the working wavelength, an effort which required using laser sources instead of vacuum tubes. HCN lasers for $\lambda = 0.337$ mm were developed by S. Dyubko at the Kharkov State University and also by Kuleshov's team at IRE NASU.

In 1980, the latter source was tested in a prototype single-channel homodyne interferometer at T-10. In addition to the laser, new components included cryogenic n-InSb detectors and a remote control unit [183]. In the 1980s, an even more ambitious and extremely expensive fusion machine was put into operation at IAE, the T-15 (Figure 15.42). Its revolutionary new feature was not the plasma camera but the superconducting magnetic system. Plasma diagnostics here were configured in a nine channel vertical sounding tomographic configuration (Figure 15.43) [184] based on the same QO components as the single-channel prototype tested previously. This interferometer was built in 1985 by combined team efforts of IAE and IRE NASU. Its adjustment was performed with special laser-beam tuning devices integrated with the angled bends and beam splitters in HDB. As the beam waveguide could operate at even shorter wavelengths, in the late 1980s another interferometer was built and operated at T-15. It was based on the $\lambda = 0.119$ mm CO_2 laser with a microwave pump, and enabled one to measure electron densities up to 2.10^{14}/cm^3 [185]. In the course of this work with the new instrument, it was

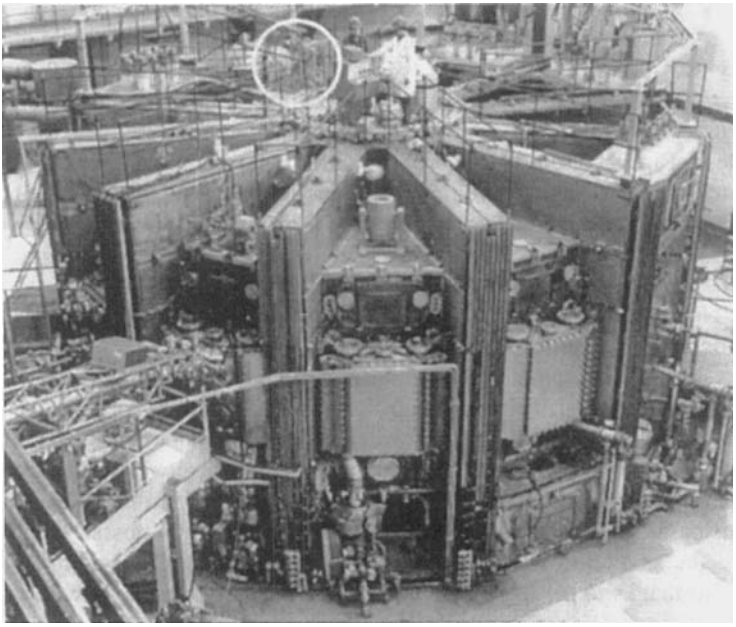


Figure 15.42. General view of the nuclear fusion machine Tokamak T-15 at IAE with a circle marking the placement of the QO interferometer (photo provided by V. Kiseliov, 1985).

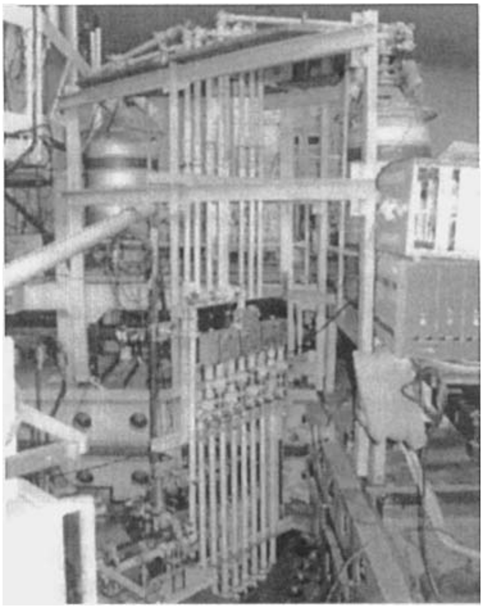


Figure 15.43. The second QO nine-channel HDB-based interferometer (λ=0.337 mm) with an HCN-laser source for hot plasma diagnostics of Tokamak T-15 at IAE (photo provided by V. Kiseliov, 1985).

shown that when a sub-mm wave beam passed through the peripheral part of the plasma column it experienced a Faraday rotation of the plane of polarization. To quantify this effect, which could yield valuable information on the plasma magnetic field, the IRE NASU team developed a prototype single-channel interferometer-polarimeter. This was the last project performed for the IAE. It was released in 1992, the last year of the USSR [186]. That December, after the independence referendum in Ukraine, the Russian government cut off financing for R&D projects carried out there. In the following year, all experiments with fusion machines at the IAE were terminated because of power shortage, and today the chance of reviving T-15 is essentially zero. Instead, a small ITER-compatible machine is being built in Moscow, assembled from the parts remaining after dismantling the T-10.

Since the late 1970s, one more mm-wave transmission line closely related to HDB and MDW has been developed. This is a circumferentially corrugated circular OSW [187, 188] with a corrugation depth equal to a quarter-wavelength. Here, the effect of the periodic rectangular grooves on the inner wall is essentially the same as of the dielectric lining in HDB and MDW. The principal mode is again the hybrid HE_{11} mode, whose ohmic losses are low as a result of the small values of the field at the walls; the higher-order modes are filtered out thanks to the high losses. The operating wavelength, however, has to be far from the Bragg reflection regime. These beam waveguides are made from stainless steel and are attractive in the high-power application as they are able to guide up to 1 MW, if evacuated [75]. In the USSR, M. Petelin and G. Denisov and their colleagues from IAP RAS in Nizhny Novgorod have been active in this field, developing various mm-wave circuit components [189-191].

15.8 BRIEF SURVEY OF MODELING METHODS AND TOOLS USED IN QUASIOPTICS

In terms of theory, sometimes it is said that QO is based on physical optics (PO) for analysis and on GO for synthesis. In fact, several major ideas, concepts, and methods have played important roles in the establishment of QO theory. Some of them relate to the description of wave beams, while the others handle diffraction of short wavelength radiation by objects of large size. There are two points to emphasize about today's tools for modeling and simulation of various QO waveguides and devices. First, most of the theories are scalar ones and study the solutions to the Helmholtz equation (or its asymptotic form in the paraxial domain - the parabolic wave equation) separately for each Cartesian component of electromagnetic vector field. Second, because of the rather large electrical dimensions of QO components (size measured in terms of the wavelength of the radiation), approximate analytical techniques still have the upper hand over rapidly expanding numerical methods. The area of electromagnetic simulation where $D > 20\lambda$ is largely inaccessible even for the Golem of today's electromagnetics: FDTD. Other specialized analytical-numerical methods, such as the method of moments, have greater impact on the low-frequency part of QO.

GO. The oldest simulation tool, GO, is the instrument of classical optical technology and considers the limiting case of $\lambda \to 0$ [192]. Here, the electromagnetic vector field is assumed to locally behave as a homogeneous transverse plane wave. This leads to the eikonal equation for the field amplitude. With GO, a beam wave is modeled as a bunch of rays, and the ray-tracing algorithms propagate these rays through the optical system and determine the field distribution on the output surface. A very important modification of GO was developed, as is well known, by J. Keller [193], who introduced so-called diffracted rays appearing due to edges, tips, corners and other surface discontinuities of the scattering body. Note however, that the range of validity of GO is determined by the approximate character of the eikonal equation. Well-known examples of its failure are focal-domain analysis and long-distance beam propagation where the problem sometimes reveals itself at moderate distances when applied in clearly QO circuits (see [70]). Besides, as do all other scalar theories, GO neglects the coupling of the vector components of the electric and magnetic fields through the boundary conditions.

In the USSR, Keller's theory was not widely known. Nevertheless GO antenna simulation tools were well developed as a result of the fundamental works of B. Kinber and his colleagues [194]. In subsequent work, GO was widely applied in the analysis and synthesis of large QO antennas including polyfocal [195] and anisotropic ones [196]. The books [66,197] covered GO-based characterization of basic microwave antennas of the lens type.

Direct PO and angular-spectrum method. At the core of direct PO lies the Huygens–Kirchhoff method based on the Helmholtz-Kirchhoff integral theorem derived from Green's theorem with the choice of Sommerfeld's uniform scalar spherical wave as the Green's function. It divides these into three domains according to the features of the diffraction field: the near zone, the intermediate (Fresnel) diffraction zone, and the far zone. In the far zone, i.e. at distances $R >> 2D^2/\lambda$, the electromagnetic field behaves as a spherical wave. In the near and intermediate zones it propagates as a beam. In the latter two zones, with a quadratic correction in the antenna aperture-field phase, one can achieve proper focusing and perform directive power transmission to the receiving antenna. The efficiency of beam forming in such a system is determined by the electrical size of the antenna's aperture and its focal distance. Besides the direct PO method, the plane-wave spectrum approach was also proposed [155] and developed [198] in the 1950s. The concept of the angular spectrum was introduced as a complex-valued function depending on the direction of the wave propagation that is the Fourier-image of the field in the aperture plane. Here, one can usually neglect the contribution of so-called "evanescent" plane waves, which are characterized by complex-valued wave numbers. To determine the power of a non-planar wave incident on a receiving antenna, simple and convenient engineering estimations were found almost simultaneously in the USSR [199] and in the USA [95] as early as in the late 1950s. This approach turned out to be useful in the calculation of the scattering losses not only in free-space Gaussian beam propagation [68] but also in QO beam waveguides, where discontinuities distort the amplitude and phase of the wave beam [141].

In the early 1960s, approximate solutions of the effects of discontinuities in OSW based on PO and GO were obtained by several scientists working in Moscow [194,200-202]. Subsequently, some of these QO circuit elements were computed at IRE NASU, Kharkov by using accurate numerical methods based on semi-inversion [203]. The comparison showed the applicability of the approximate methods, within an accuracy of 10%, if the waveguide size satisfied the condition $D > 5\lambda$. Using PO, diffraction of the HE_{11} mode from local scatterers in HDB was considered in [167,169].

Parabolic-equation technique. The "paraxial approximation" implies that any field component can be written as the product of a plane wave propagating along a definite direction and a slowly varying "wave amplitude". This amplitude has to satisfy the parabolic wave equation as a paraxial form of the Helmholtz equation. In the late 1960s and 1970s, many remarkable studies were published based on this asymptotic technique, most notable being the papers on the modes of open resonators. In fact, a satisfactory explanation of resonators made of two flat or curved mirrors had been the main driving force behind the early development of Gaussian beam theory. In the USSR, the book [204] authored by L. Vainshtein covered various infinite two-mirror resonators in the scalar paraxial approximation, and marginally treated "open waveguides" of reflection and lens type. The publications of Katsenelenbaum [24,25,205] and Talanov [206,207] had much greater impact on QO practice, as they directly developed the Gaussian beam approach.

PTD. In the mid-1960s P. Ufimtsev published the method of edge waves, also known as the physical theory of diffraction (PTD) [208]. He introduced into PO the concept of secondary waves originating from currents at the edges, bends and other discontinuities on the scatterer's surface. This empirical approach later was partially justified. It enabled researchers to obtain concise representations for the electromagnetic fields scattered by objects of large size and complex shape. In the 1990s, PTD became generally recognized as an efficient and economic approach in the design of stealth aircraft and ships having reduced RCS signatures.

Gaussian Beams and the Paraxial Approximation to the Angular Spectrum Method. As was discussed in [17], the theory of Gaussian beams may be obtained from various starting points. For example, a fundamental solution of the parabolic equation in the free space is the Gaussian beam. In this manner, in [139], Goubau studied the angular-spectrum PO approach in the paraxial approximation, enabling him to obtain the field as a sum of Gauss-Hermite functions (in a Cartesian coordinate system) or of Gauss-Laguerre functions (in a cylindrical coordinate system). The characteristic parameters - beamwidth (or the field spot size) and phase front radius of curvature have convenient and clear physical meaning. Even more important is that the field expansion as a Fourier integral enables one to consider the beam transformation in various QO systems by using a sort of the scattering matrix technique [209,210]. This approach to wave beam propagation, together with the GO ideas of phase correction, takes into quite accurate account the diffraction effects associated with large-sized lenses and reflectors. Later J. Arnaud [211] and A. Greynolds [212] greatly enhanced this approach by introducing the decomposition of a field distribution on an aperture into a set of spatially confined fundamental Gaussian beams of at least 100λ width. This eliminated the need for intermediate GO propagation, and enabled one to compute the wave propagation between two surfaces very efficiently.

Complex-Source-Point Concept. This is another, and very elegant, way to introduce the beam-like field solutions of the full-wave electromagnetic equations. Although many authors touched it in the late 1960s, G. Dechamps is frequently credited for suggesting that one could add an imaginary component to the radius vector of the source point and obtain waves that behave as directive beams [213]. Interestingly, a similar paper published in the USSR a year earlier [214] went unnoticed. In the paraxial domain of the near zone, the complex-source-point (CSP) beam behaves as a Gaussian beam, while in the far zone it is an outgoing spherical or cylindrical wave. The CSP field can be taken as an incident field in the analysis of any scattering problem. Then, given a solution to the similar problem for "real-source-point" excitation, one should modify it by inserting the corresponding complex-valued parameters. In the 1970s, Felsen and his colleagues published many analytical studies of this sort, treating beam scattering by flat material interfaces and slabs [215]. This idea was later implemented in numerical analyses of reflectors with the aid of asymptotic GO [216] and accurate analytical regularization [217] approaches. Despite mathematical complications (the appearance of finite-size real-space branch cut in the CSP field function), and the inability to simulate radiation blockage by the feed, the CSP beam is clearly a step ahead of the simplified Gaussian beams, which satisfy only the parabolic equation.

Vector Theories. It is quite clear that in order to obtain the most accurate results one must use a vector form of diffraction theory based on Maxwell equations, exact boundary and edge conditions, and exact distances instead of approximations. The first satisfactory vector approaches to the electromagnetic scattering problem were formulated by F. Kottler [218], and then by J. Stratton and L. Chu [219]. The Gaussian beam decomposition formulation was extended to the vector case in [220]. Vector forms of CSP beams are straightforward and equally easy to handle – they imply adding an imaginary term to the real space location of an elementary dipole or a Huygens source. The corresponding field functions still are exact solutions to Maxwell's equations in the whole space considered. This approach has been successfully applied to the analysis of open resonators [221] and spherical-reflector antennas [222].

Modal Expansions and Mode Matching. Expansion of the electromagnetic field in a closed metallic waveguide in terms of a modal series has been known since the pioneering work of Lord Rayleigh around 1900 [223]. The analysis of wave propagation leads here to the eigenvalue problems in which one has to find a discrete set of real or complex valued propagation constants for the natural modes of a regular waveguide. The guided mode theory of closed metallic waveguides was developed in the 1940s and 1950s. Stratton was probably the first to consider the natural propagation modes of a circular cylindrical channel in an infinite dielectric [155]. He used separation of variables and derived generic dispersion equations. In 1964, E. Marcatili and R. Schmeltzer studied the same structure [154] in more detail assuming that the radius of the channel was large. They determined the natural modes together with their propagation and attenuation constants. The self filtering effect was noticed and explained by the greater absorption of higher order natural modes. The lowest hybrid natural mode HE_{11} having the minimum attenuation was even recommended for possible application in longdistance optical communication. Although this idea was later discarded in view of obvious success of optical fibers, propagation of waves in hollow channels was studied for the other applications. Interesting numerical data on the modes in a lossy tunnel were published in [224].

The mode-matching technique (MMT) is a widely known numerical-analytical method of solving the scattering problems associated with closed resonators and waveguides. Since the 1970s, it has been applied to study the effects of irregularities such as bends and steps in OSW. Here, economic algorithms having guaranteed convergence were developed in the 1970s and 1980s in IRE NASU, Ukraine [203, 225] and in the Rostov State University, Russia [226]. They were based on the concept of semi-inversion or analytical regularization and enabled a rigorous check of the validity of previously known asymptotic GO and PO solutions for angled bends, U-turns, steps and OSW cavities.

Grating Theories. Theoretical analysis of electromagnetic wave scattering by periodic scatterers such as wire grids and diffraction gratings cut in a metal plane was carried out by many researchers and has a long history since the pioneering papers of H. Lamb [227] and Lord Rayleigh [228]. In QO components, as is clear from the review presented above, two types of periodic structures are commonly used: free standing wire grids and flat metal-strip gratings deposited on dielectric slabs. This is because the most valuable property of gratings for QO instruments is their polarization selectivity. This occurs provided that the grating elements are metallic and that their period is less than one fifth of the wavelength, i.e. they can produce only zero-order scattering. Higher order scattering does not see much practical use; hence the application of gratings in QO is significantly different from that in traditional optics. In consequence, quasistatic theories of single order scattering of plane waves from gratings are of primary importance. In the USSR, Vainshtein of the IPP RAS was a pioneer in this area when he published, in 1955, a paper on the Wiener-Hopf solution to the PEC flat strip grating [229] not knowing that the same solution was published just one year before in [230]. His later paper [231] and papers of V. Yampolsky [232] can be credited with presenting the theoretical estimates of the reflectance and transmittance of PEC wire grids having period p in the range $2b < p << \lambda$, where $2b$ is the wire diameter. These works duplicated in part similar publications in the West [233-235]. Later, similar and more accurate expressions (in the USSR, they were usually called Lamb-type formulas) were obtained by several researchers in Kharkov for a wider class of diffraction gratings including imperfect wire grids and PEC flat strip gratings [225,236]. Here, the technique was a semi-inversion method with analytical inversion of the static part of the scattering problem that led to explicit solutions in the small-period case. These analyses revealed that realistic wire grids made of copper or tungsten could be still simulated as PEC ones at sub-mm wavelengths provided that $p < 0.2\lambda$, as the absorption did not exceed 5% even with the E-field vector parallel to the wires. These conclusions were supported by experimental measurements [237]. Later the semi-inversion method was used in [238] to obtain Lamb-type formulas for the free-standing gratings made of resistive and dielectric flat strips. The theories that had been developed remained valid for higher-order scattering as well, where a numerical study was imperative. This led to several interesting proposals about using the gratings of the groove and echelette type in the blazing mode, e.g., to provide additional resolution in open resonator spectra. A later book [239] included several examples of Gaussian beam scattering by infinite perfectly conducting strip grids.

Numerical Methods. There exist many numerical methods that can potentially be used in the analysis and design of QO components and devices. We will not discuss them in detail. However, we would like to emphasize that almost all of them either loose accuracy in the range of the characteristic QO relationship between the wavelength and the size of the scatterer, or lead to high numerical complexity of the algorithms and hence prohibitively large computation times. Therefore, one will look in vain for the frequency dependence of the gain of a reflector or lens antenna of realistic size computed with the method of moments or FDTD. There is, however, at least one full-wave analytical-numerical approach that is able to reach the true QO range of the size-to-wavelength ratio while maintaining high accuracy and reasonable computation time. It is referred to as the semi-inversion or analytical regularization method (MAR), developed primarily in the USSR by the groups of scientists in Kharkov, Rostov, Lvov, and Moscow since the early 1960s. Several researchers in Greece, Italy, Japan, and the USA also made significant contributions - see [240]. At the core of this approach is the idea of analytical inversion of the "worst" part of a singular integral equation equivalent to the Maxwell problem. This invertible most singular part is associated either with the static limit or with a canonical regular shape (circular cylinder or sphere) or with the high-frequency limit (actually, again a canonic scatterer, however a specific one – the halfplane). The resulting matrix equations that are generated by such an approach are always very small – just slightly larger than electrical size of the scatterer, and have favorable convergence features. At first, this approach was extensively used in the analysis of gratings and discontinuities in OSW [203,225], and then it was applied to other problems [239]. MAR based on the static part or canonic shape inversion encounters no computational problems when solving 10-100 λ reflectors and lenses in the QO domain [222]. However, it is more economical if based on the inversion of the high frequency scattering operator parts relating to the semi-infinite fragments of scatterers. This variant of MAR is much less developed than the others, and the known solutions are restricted to the flat strip and flat disk scatterers [241-243]. If extended to curved and combined scatterers, it can become an extremely efficient and accurate tool for computational electromagnetics in QO applications.

15.9 NEW FRONTIERS OF THE XXI CENTURY: OPTICS GOES QUASIOPTICAL

QO has been one of the important areas in millimeter wave and sub-mm wave science and engineering from the time of Hertz's first experiments to the present. It includes the methods of transmission of electromagnetic power, the principles underlying functional elements, the experimental methods of physical research, and analytical and numerical simulation tools. The scientists of the former USSR made significant contributions to fundamental and applied research related to mm and sub-mm waves. From the information that has been presented here, one can see that the main QO laboratories were established by the USSR Academy of Sciences and concentrated in Moscow, Kharkov and Nizhny Novgorod. The *Microwave Pioneer Award* of the IEEE Microwave Theory and Techniques Society given in 2000 to the Ukrainian scientist Yevgeny Kuleshov caps the recognition by the world scientific community of this contribution. His citation reads, *"For the development of a hollow dielectric beamguide technology and measuring technique of the short-wave part of millimeter and sub-millimeter wave ranges"* [244].

In the XXI century, QO has new and exciting frontiers mainly in the shorter than millimeter wavelength portion of the electromagnetic spectrum. These frontiers are set, on the one hand, by the amazing opportunities given by the available computer hardware and software, and, on the other hand, by the rapid development of terahertz technologies and optoelectronics. It can be expected that more and more sophisticated QO systems will appear, with development aided by computer design tools based on more accurate vector solutions. For example, today terahertz-range antennas show an example of new synergy between QO and quasistatic principles (the first was the application of small-period grid polarizers in QO beam waveguides). Here, microsize printed elements and coupling lines are integrated with lenses to boost the efficiency and sensitivity, and to provide beam collimating and focusing [245,246].

Remarkably, even the areas traditionally governed by classical optics have come to the point where comprehensive account of diffraction phenomena is possible and desired in order to improve system performance. This is the case, e.g., for optical and near-infrared astronomical observations, with large integration times, of faint objects. In 1997, the work stared on the Very Large Telescope Interferometer (VLTI) international project, with the ultimate goal of computer-controlled coherent combination of signals from the four "unit telescopes" (diameter 8.2 m) and several movable "auxiliary telescopes" (diameter 1.8 m). In 2001, the first stellar observations were undertaken with this interferometer. At a wavelength of 2μm, effective propagation distances reach 200 m resulting in significant diffractive spreading of the starlight beam several cm in diameter; hence beam clipping and general deviations from GO behavior are inevitable. The way to achieve the ultimate performance is seen in high-precision steering and tuning the variable-curvature (pressurized) mirrors included into a control loop and aided by computer analysis of beam propagation provided by the *BeamWarrior* software package [247]. This combines several different methods in the common framework of scalar diffraction theory: direct

PO field computation and angular-spectrum methods (both with and without the paraxial approximation), and a Gaussian beam decomposition technique able to compute "end-to-end" wave optical propagation. In the latter case, the typical waist size of the elementary beams considered is 1300λ. This software package is the most powerful tool available today for computing quasioptical fields, including polarization effects, if both the apertures and the observation distance from the apertures are large compared to λ. Thus the right-hand side boundary of "QO strip" in Figure 15.1 is shifting to at least $D \approx 10^4 \lambda$.

At the opposite end of the chain are light-emitting components, devices and instruments, having typical dimensions not much larger than a wavelength. Hence, accounting for the QO effects in the light propagation, confinement, and scattering is mandatory for improvement of existing technologies. For example, comprehensive modeling of vertical-cavity surface-emitting lasers (VCSELs) to enhance the performance of these complex light sources is an active R&D topic. Recently it was found that beam confinement and threshold reduction achieved in VCSELs with oxidized windows can be correctly explained by assuming that the mode field has the shape of a Laguerre-Gauss beam [248]. Therefore it is no surprise that one of the most efficient ways of polarization selection of the VCSEL modes is to use a metal grid placed on top of the output aperture [249]. There is little doubt that this approach will be further extended, and that finer diffraction effects are accurately taken into detailed account in the design of mm-wave, terahertz, infrared, and optoelectronic devices and systems satisfying QO criteria.

Exciting opportunities for the design of revolutionary new QO components and instruments are offered by emergent technological innovations, such as electromagnetic bandgap materials and metamaterials (also known as twice-negative and left-handed materials). For example, a QO prism made of bandgap material may display frequency and angular dependence of the incident beam deflection one hundred times stronger than that of a similar homogeneous prism [250]. Exotic designs of new QO lens antennas and beam waveguides made of metamaterials can be based on interesting effects including negative refraction [251]. Therefore the future of quasioptics is perfectly secure as long as electromagnetic waves are still used by the information society.

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