Reverberations

Early Quasioptics of Near-Millimeter and Submillimeter Waves in IRE-Kharkov, Ukraine: From Ideas to the Microwave Pioneer Award

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In 2000, Ukrainian scientist Yevgeny M. Kuleshov was awarded the Microwave Pioneer Award from the IEEE Microwave Theory and Techniques Society. He received it for the development, in 1964–1972, of the hollow dielectric beam-waveguide (HDB) technology and measuring techniques of the near-millimeter and submillimeter wavelength ranges, with main application in hot plasma diagnostics (Figure 1). Yevgeny M. Kuleshov was born in 1922 in Voronezh, now Russia. In 1946, he became a postgraduate student of A. Slutskin at the Ukrainian Institute of Physics and Technology (UIPT). Starting in 1949, he worked in the UIPT department of electromagnetic oscillations, and headed the laboratory of receiving and measuring devices there from 1953 to 1955. In 1957, he earned his Ph.D. degree. After IRE branched off of UIPT in 1955 and until 1988, he headed the department of QO there; now he is a leading scientist. Besides the awards mentioned here, he holds the title of Honorary Inventor of USSR (1989). This is recognition of the great contribution done by Kuleshov and his team [1] of the Institute of Radio Physics and Electronics of the National Academy of Sciences of Ukraine (IRE NASU, Kharkov) to the quasioptics (QO) of millimeter and submillimeter waves. Together with a few laboratories in Moscow and Nizhny Novgorod, IRE-Kharkov had become a major USSR center in this area of R&D already in the late 1940s when first A. Slutskin [2] and then his colleagues worked there on millimeter-wave magnetrons. Already in 1960, a team of IRE staff including Kuleshov was awarded a Lenin Prize, the most prestigious in the Soviet Union, for the development of various millimeter-wave devices and techniques. It should be emphasized that Kuleshov and his colleagues for years had been on the practical side of R&D, and most of their technical reports remained classified as done for the USSR Committee for Atomic Energy (CAE), Ministry of Radio Industry (MRI), and Ministry of Defense (MD). A chapter [3] written by Kuleshov, thanks to the insistence of the book editor, was a rare exception. Therefore, we would like to present here some details of this activity based on the declassified reports and the interviews of Kuleshov and another key member of the QO team, Moisei S. Yanovski [4]. (Moisei S. Yanovski was born in 1923 in Kiev, Ukraine. After graduation from KPI, he was a Ph.D. student of A. Slutskin in UIPT and earned his degree in 1954; since 1955, he has been a senior scientist in IRE and participated in all projects of the QO department.) In addition, papers [5]–[9] were valuable sources of general information on QO.

Short Survey of the Millimeter-Wave Quasioptics

It should be noted that H. Hertz and his followers, notably, millimeter-wave pioneers P. Lebedev in Moscow and J. Bose in Calcutta, already used basic QO principles in 1888–1900 [6]. At that time, parabolic reflectors, dielectric lenses and prisms, and other essentially optical devices were successfully used to demonstrate the common nature of the “ether waves” and visible light. Not surprisingly, this science was then called “Hertzian optics.” However, despite initial enthusiasm, the following years showed an abrupt decay in the R&D of microwave. A part of the reason was that the only available sources, spark-gap ones, were not practical. More substantially, rapid progress of the radio diverted the interest of researchers, the public, and the military to much longer waves. The next, and the main, period of progress in microwaves and then millimeter waves came in the 1940–1970s. Breakthrough was achieved thanks to the invention of the multicavity magnetron oscillators and generous military funding of radar R&D. Both Kuleshov and Yanovski graduated, in 1946, from a Kiev Polytechnic Institute class of S. Tetelbaum (1910–1958). This remarkable young professor developed an early gyrotron oscillator, studied microwave wireless power transmission, and became enthusiastic about a city bus supplied with microwaves beamed from a distance. A great fan of microwaves, he tried to infect his students, including future inventors of HDB, with this virus. Now one can see that he was successful in doing so.

By the end of the 1950s, centimeter- and partially millimeter-wave ranges had been explored. A general trend was to switch to higher frequencies beyond microwaves, where QO principles promised lower losses and had obviously better validity. This implied using electromagnetic waves in the form of beams having effective spot size w greater than the wavelength λ, however, smaller than the dimensions of scatterers or cross sections of waveguides, $D : \lambda < w < D$. As, however, D could be just several λ, a joint account of both ray and diffraction phenomena was necessary. The term "quasioptics" was apparently coined by E. Karplus in the United States in 1931 [10] and then forgotten for 30 years, although a parallel term "microwave optics" was used in the 1950s. Here, QO principles were successfully applied in the reflector and lens antenna technology. Finally, L. Felsen, who was a prime organizer of the famous symposium held in the Polytechnic Institute of Brooklyn, New York in June 1964 [11], should be credited for giving a firm ground to QO. The following year a translation of symposium proceedings into Russian was initiated in Moscow [12]. It was printed as a book *Kvazioptika* (Figure 2), which soon became a bible for the USSR millimeter-wave laboratories. Three years later, this term was routinely used in the book [13], which summarized the USSR experience. The 1960s were the "golden age" of QO and witnessed numerous attempts of designing various new transmission lines. The first idea was to use simply a directed wave beam propagating in free space between the transmitting and receiving antenna. Gaussian-beam elements were added early on to a designer's arsenal for making various laboratory-measuring systems, foremost for spectroscopic analysis [8], [9]. In parallel, an alternative QO technology was proposed: completely closed metallic oversize waveguides (OSW), thanks to reduced attenuation as compared with standard waveguides. By 1963, components based on rectangular OSW with the wave H_{10} that worked at the frequency up to 350 GHz were developed.

A few years later than OSW, two compromised design ideas emerged: discrete (open) beam-waveguides formed by periodic lenses, irises, or reflectors, and continuous (closed) beam-waveguides shaped as OSWs with lossy-dielectric, layered-dielectric, or metal-dielectric inner walls. The latter lines were later referred to as HDB and metal-dielectric waveguides. Two common points exist for each of them. Each system works with a corresponding principal mode while the higher order ones experience increased radiation or absorption. Besides, the principal mode itself is either a classic QO Gaussian beam or a mode whose field is close to such a beam, like in HDB. Thus, the principles of the field confinement in the cross section and self-filtering are basic ones. The idea of periodic phase correction of a free-space microwave beam, to compensate for its divergence, was very natural. G. Goubau authored the first publications on the periodic lens and iris transmission lines in 1961 [14], [15]. Within the next several years, active R&D in this area took place both in the West and in the Soviet Union. V. Shevchenko at the Institute of Radio Engineering and Electronics (now IRE RAS, Moscow) patented a waveguide with lenses inclined at the Brewster angle to the axis, to reduce the reflections [16]. In 1963, B. Katsenelenbaum of IRE-Moscow published a periodic reflector beamguide [17] just a half-year before J. Degenford [18]. Competition between open lines has left the victory to the reflector beam waveguide, still in use today for antenna feeding and plasma

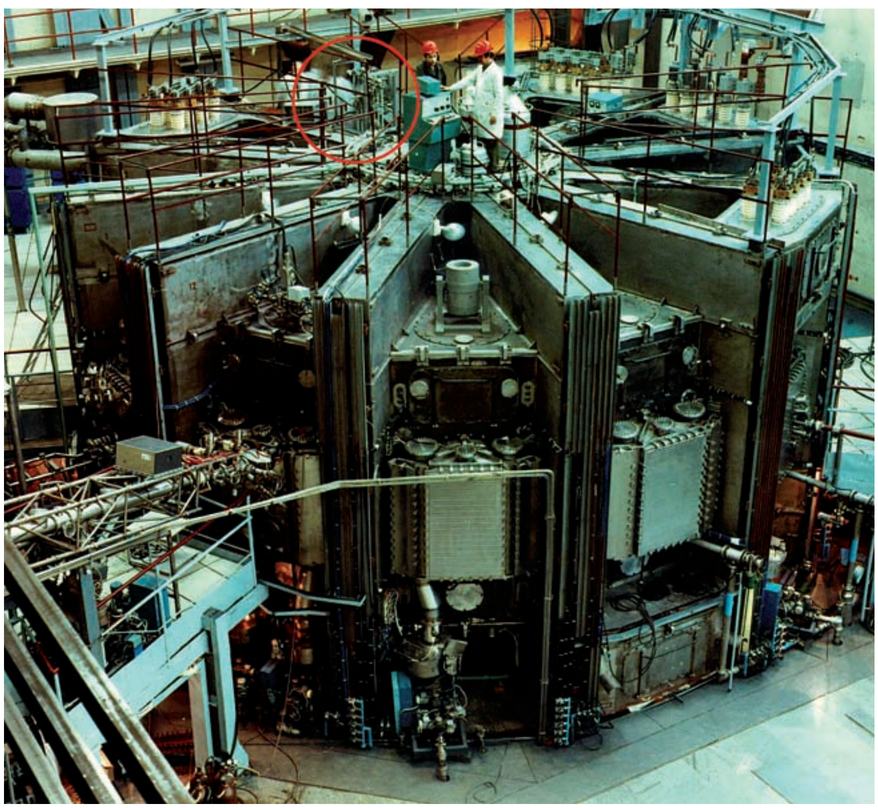

Figure 1. *1988. Tokamak T-15, the USSR nuclear fusion machine with superconducting magnetic system. The array of QO beam waveguides forming interferometer for plasma sensing is marked with a circle.*

heating. As for the HDB, one of the pioneering and most known in this field was a theoretical study published in 1964 by E. Marcatili and R. Schmeltzer [19]. They considered in greater detail the structure first solved by J. Stratton in his *Electromagnetic Theory,* i.e., circular cylindrical channel in unbounded dielectric medium, and found out that it could support quasi-single-mode propagation. Independently and half a year earlier, Kuleshov selected a similar channel when designing a new basic transmission line for a set of wide-range millimeter- and submillimeter-wave measuring circuits [20].

It must be noted that in the area of long-distance communication, the time of the millimeter waves was over in the early 1970s when optical fibers came into being. Besides periodic attempts to develop millimeter-wave battlefield radar, two nondefense applications became a driving force in QO: spectroscopy and nuclear plasma diagnostics. The first attracted attention in the West, whereas the second in the Soviet Union, in part because of the obsession of its political leaders with nuclear fusion that was based on the invention of the Tokamak principle.

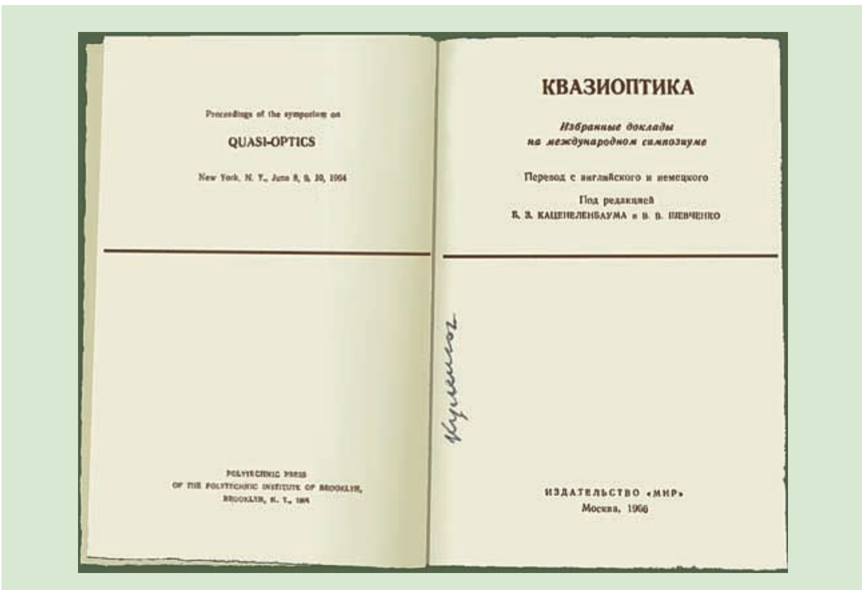

Figure 2. *1966. Title page of the* Kvazioptika *book bearing the signature of Kuleshov.*

Figure 3. *1962. A meeting of the IRE Scientific Board. Kuleshov is the second from the right in the front row. Braude is behind him in the fourth row, second from the right. At the time of Gagarin's flight and the Cuban missile crisis, the military was frequent at such meetings.*

Emergence of the HDB Concept

Between 1954 and 1961, Kuleshov and his team had already accumulated rich experience in developing waveguide measuring devices in the whole millimeter-wave range. By that time, ordered by the 5th Chief Directorate (CD-5) of MD, a series of projects had been performed [21]–[24] with the small-size single-mode waveguides for $\lambda = 4.1$ to 1.7 mm. In addition, since 1958, the Institute of Atomic Energy (IAE, Moscow) of the CAE was allocating generous funding to IRE for the development of millimeter waveguide interferometers for the Tokamak plasma diagnostics [4], [25]. Additionally, another project funded by CAE was in progress in 1963–1964, on an interferometer for $\lambda = 1.5$ to 2.2 mm and a set of radiometers, based on the 0.55×1.1-mm waveguide [26]. Here one remarkable episode was relevant to the destiny of QO in IRE. According to Kuleshov [4], some day in 1962 the IRE Scientific Board was hearing his report (Figure 3). After presentation, then deputy director of IRE academician S. Braude (1911–2003) critically remarked about this research. He pointed out that the team worked mainly on scaling the existed standard-waveguide technologies. However, due to the greater losses, this way of moving to shorter wavelengths was clearly a dead-end. He advised to look for the new design principles and, in particular, to pay more attention to the optical methods.

In fact, Braude's words only increased the motivations to explore the QO opportunities. By that moment, the QO methods of electromagnetic wave transmission and processing had became increasingly popular. That was the time when the first papers of Goubau on successful periodic QO beam-waveguides were published. The main question was how to adapt QO to the existing and expected applications. The periodic waveguides were quite specific and much different from the single-mode waveguide, because their beam phase-front and diameter varied along the axis. How this affected the characteristics of components was far from clear. Besides the published descriptions of such waveguides, IRE designers were acquainted with a similar work done in another Kharkov R&D organization, Institute of Metrology (RDIM). Around 1963, a research project was performed there dealing with QO components for a lens waveguide. The main results of it were published in 1969 [27]. It was guided by A. N. Akhiyezer (1928–1996), a colleague of Kuleshov and Yanovski before 1953. Unlike conventional lens line, he had placed his system into an aquadag-impregnated paper tube with longitudinal ribs glued to its inner surface for rigidity. Characteristics of such a beamguide were similar to those of the Goubau line, whereas the absorbing paper tube decreased unwanted reflections. Both Kuleshov and Yanovski were external jury members for the RDIM projects. According to them, Akhiezer's work can be regarded as one of the first attempts to make a kit of QO radiometric devices in the 4-mm range. However, he used a mixed approach and combined in one circuit the sections based on the lens waveguide and those based on the standard hollow one, with bulky and lossy transformers.

In contrast to this, the IRE team was suspicious of the open-periodic beamguides. To the opinion of Kuleshov, requirements to the new transmission line had to be as follows: no periodic variations in the field amplitude and phase along the axis, linear field polarization, symmetry of the field with respect to two orthogonal directions in cross section, self-filtration of the higher order modes, low attenuation of the principal mode, wide operation frequency range, strong shielding, and eventually mechanical integrity of the structure. All of the mentioned points appeared quite naturally as a result of the earlier involvement into research of IAE [25]. Tokamaks used to work in the pulsed mode and experience powerful vibrations. Therefore, millimeter-wave interferometers for precise measuring of the electron density of the hot plasma had to provide a rigid coupling between the sections of transmission lines and measuring units.

The whole of 1963 was spent in a search for available information around QO circuits and selection of appropriate basic concept. In parallel, Kuleshov was busy finding a source of funding for such innovative and risky R&D. In 1963, he had no vision, though, that new technology could be in great demand at the next stage of the nuclear fusion research. He worked on the submillimeter waveguides guided solely by his intuition and scientific interest. Demand from IAE for the QO circuitry was yet six years ahead, as they were still mastering Kuleshov's millimeter-wave interferometers built with standard waveguides. Of course, the IAE leaders knew that only a larger plasma camera, of about 1-m diameter, was able to provide sufficiently stable and dense plasma. Such plasma could be sensed only with submillimeter waves. However, in 1963, they simply had no large Tokamak and were not yet interested in the shorter waves. Therefore, Kuleshov correctly guessed that a sooner response might be received from defense-oriented MRI. In particular, the chief engineer of CD-6 V. Dubenetsky was known for his very high estimation of Kuleshov's fine work on millimeter-wave waveguide measuring techniques. In 2003, Kuleshov remembers quite clearly how he came to the HDB concept [4]. As a less lossy alternative to the lens line, an iris line was known; however, typical of all periodic beamguides, it displayed a variation of beam parameters along the axis. When analyzing how small the spacing could be between irises in absorbing screens, he considered a limiting case of period reduced to zero. Surprisingly, such a line demonstrated good guidance characteristics that caused the choice in favor of lossy dielectric tube. At the end of 1963, having done preliminary estimations and experiments, they formulated a proposal and submitted it to Dubenetsky. After a short discussion, the contract was signed on 30 March 1964.

Research Project "Ozero": A Milestone

The aim of "Ozero" was to explore the feasibility of developing a kit of HDB-based measuring devices in the wavelength range $\lambda = 0.7$ to 1.7 mm. The project was carried out in 1964–1966 with Kuleshov as a principal investigator [20]. The IRE team also included M. Yanovski, D. Litvinov, B. Knyazkov, N. Tolmachev, V. Scherbov, B. Panchenko, V. Bryzzheva, A. Goroshko, L. Yegorova, L. Kochetova, V. Stenko, V. Savchenko (Figure 4), and a number of technical personnel. Initial works were performed by using the waveguide measuring circuitry and vacuum sources of the 1.5-mm range developed in IRE [26]. As preliminary information, all available data on the existing QO transmission lines have been put together and systematized, and the methods of building the key functional elements and measuring units were reviewed. This section of the "Ozero" report had 100 pages with about 40 figures and 185 references and looked like a perfect handbook on QO principles in microwave engineering. Unfortunately, the work was given a classified status, and the authors were not allowed to publish any part of it, even of general character. It is interesting to note that the basic configuration of HDB had been chosen without in-depth theoretical analysis, just from engineering intuition and rather approximate estimations. Still this choice turned out to be absolute success. The next two stages of "Ozero" were performed in 1965–1966, already after the paper [19] had been published in the *Bell Systems Technical Journal* and reached the IRE library. On reading this study, Kuleshov and his colleagues felt that they finally had a theory supporting their choice of the basic QO transmission line. It enabled them to see the role of characteristic dimensions of HDB and its dielectric parameters. Still, however, the effect of longitudinal ribs on the inner HDB surface (introduced by them) had to be studied experimentally, as well as performance of irregularities serving as functional components.

The choice of the proper dielectric material and the tube size turned out to be very important. To minimize the losses of the principal mode HE_{11}, the dielectric constant should be ε =1.3–1.5. At the same time, with a reasonable and technically feasible thickness of the tube, the dielectric losses should provide a substantial damping of higher modes and eliminate the influence of the external metal wall. Therefore, designers selected a phenoplastic tube having tan $\delta = 0.04–0.08$ at $\lambda = 2.17$ mm. They also found that triangular longitudinal ribs provided a reduction of effective dielectric constant from $\varepsilon = 2.3$ to 1.5. The dielectric thickness of 5 mm was enough to satisfy all engineering requirements. In fact, two types of beam waveguides (Figure 5) were developed, having the inner channel diameter of 40 and 20 mm (HDB-40 and HDB-20), and designed for the wave ranges of $\lambda = 1.5–3$ mm and $\lambda = 0.7–1.7$ mm, respectively. In both cases 5-mm-thick, 60-mm-long sections of phenoplastic tube were made by pressing technology and then inserted into the sections of metal tube of varying length (from 25 to 1,000 cm). Dielectric sections were of two types, with a smooth inner wall and with a ribbed one. In the latter case, the cross dimension of the ribs were as follows: height 3 mm, base width 2 mm, Step 2 mm (for HDB-40), and height 1 mm, base width 0.7 mm, step 0.7 mm (for HDB-20). The ring flanges, fixed by clamps and centered pins, provided the coaxiality of the connected elements with the error not worse than 0.02 mm. Measurements of the attenuation and field pattern in the cross section of a smooth HDB were in good agreement with [19]. It was also shown that attenuation of the principal mode HE_{11} in the ribbed waveguide was slightly greater than in the smooth one (3.6 dB/m against 1.9 dB/m for HDB-20 at $\lambda = 1$ mm, and 2.8 dB/m against 1.5 dB/m for HDB-40 at $\lambda = 2.5$ mm). However, the higher modes were suppressed more efficiently; in particular, for a blend of modes $EH_{11} + HE_{31}$, this difference was found about 10 dB/m.

Figure 4. *1965. The staff of Kuleshov's department at the time of the first project "Ozero" on QO circuitry.*

Based on HDB, they developed over 20 new QO components, namely, waveguide-to-beamguide transitions, rotary junctions, beam splitters with a semitransparent dielectric plate, corner reflectors, transmission and reflection-type wavemeters based on Fabry-Perot open resonators, absorbing attenuators, polarization attenuators, phase shifters, thermistor mounts, absorbing loads, movable loads, movable reflectors, and so on [20]. Certainly, this was only a start, focused on preliminary physical analysis and pilot designs. Despite a pressure of time (nine months for the first stage) and lack of experience in developing QO devices, in this work, they determined the mainstream and found many bright engineering solutions later successfully implemented. Crossing the known QO concepts with HDB required close inspection of corresponding electromagnetic characteristics; therefore, the emerging combinations of components and units in complex circuits were innovative and full of creative insights. Kuleshov and Yanovski played a leading role in the engineering of all HDB-based measuring devices. Additionally, B. Knyazkov (1928–1998) suggested many smart ideas, whereas experimental studies on the beam splitters and other units were the competence of D. Litvinov (1921–2001).

The team, by their initiative, made also a feasibility study of using the periodic structures as HDB polarizers [4]. Polarization discrimination by wire grids was regarded as very promising for enriching the functionality of the developed devices and improving their characteristics. Indeed, in 1888, Hertz showed that a wire grid with small period $l (l \ll \lambda)$ reflected the E-polarized wave and was transparent for the H-polarized one. In the microwave range, a metallic grid was quite easy to implement by using either printed elements or wires. However, in the near-millimeter- and submillimeter-wave ranges, the wire diameter and periodicity should be several micron and several dozen micron, respectively. This required a specialized technology and precise instruments, which were not available at IRE-Kharkov in 1964–1966. In the second half of 1966, however, the friends from Moscow lent two grids having the tungsten wire diameter of $2b = \mu$m and period

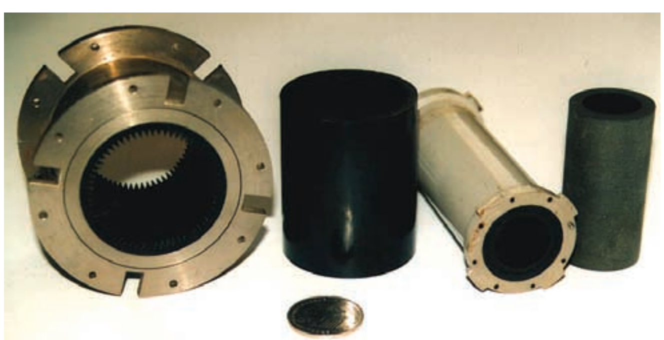

Figure 5. *1965. Short sections of HDB-40 and HDB-20 with separately shown ribbed phenoplastic inserts.*

of $l = 60\ \mu$m. Polarizers made with these grids demonstrated high performance. Namely, in the whole operation range, the minimum attenuation did not exceed 0.2 dB, whereas the maximum attenuation was 40 and 33 dB at the long-wave and short-wave ends of this range, respectively. After this work, the advantages of HDB polarization components became evident.

Research Project "Oliva": A Gold Mine

After the finish of "Ozero," Kuleshov had a break in direct funding of QO research because of the lack of immediate customers. It was only in 1968–1971 that the next R&D project called "Oliva" was granted by the same directorate of MRI. Its idea was to dwell on and refine the polarization principles in the measuring circuits for $\lambda = 0.5$–0.8 mm [28]. Incidentally, this precisely corresponded to the band of a high-power vacuum tube called "clinotron" (a version of BWT) successfully developed in IRE at the same time. When IAE's Tokamak department started building a large fusion machine in 1969, both clinotrons and beamguides were demanded from Kharkov. According to Kuleshov and Yanovski [4], they knew about the experiments with grid polarizers in the microwave laboratory of academician P. Kapitsa (1894–1984), Nobel Prize winner, at the Institute of Physical Problems (IPP RAS). In addition, attempts to create laboratory system for millimeter-wave spectroscopy were undertaken in 1967 in the P. Lebedev Physics Institute (LPI RAS, Moscow) by the initiative of the academician A. Prokhorov (1916–2002), also a Nobel Prize winner. Here, a team led by N. Irisova designed a number of Gaussian-beam wire-grid elements in the 2-mm band [29]. The major circumstance was that, jointly with the Central Design Bureau of Unique Instrument-Making of the Academy of Sciences, LPI had developed a technology of making tungsten-wire grids tightened on a metal-ring frame. Predictions of the transmission and reflection of waves by wire grids were obtained by using perturbation-theory formulas derived in 1963 by L. Vainshtein (1920–1989; see Figure 6) of IPP RAS for the plane-wave incidence in the case of perfectly conducting wires of $l/\lambda \ll 1$, with additional condition $2b/l \ll 1$ [30]. It appears that the earlier Western papers dealing with imperfect wire grids [31], [32] were not known in the Soviet Union, as only the work of V. Twersky [33] was cited in [28]. The range of validity of Vainshtein's expressions was not clear and needed a theoretical estimation. Besides, Kuleshov was interested in metal-strip grating on dielectric substrate, as a possible alternative to wire grid. In 1965, he gave a small subcontracting procurement to V. Shestopalov (1923–1999), then professor at the Kharkov University of Radio Electronics, for theoretical study of such a grating. Therefore, in 1968, the latter, already head of the theoretical electronics department of IRE, joined the "Oliva" project with his own team consisting of S. Masalov, V. Sologub, and A. Kirilenko. The task of the theoreticians was analysis of grids made of metallic circular and rectangular cylinders with finite conductivity. Unlike HDB components, the results of this study were published already in 1973 as Chapters 3 and 4 of the book [34]. In particular, it had been shown that Vainshtein's formulas had accuracy within 10% provided that $2b/l < 0.25$ and $l/\lambda < 0.5$, and effect of losses was negligible for copper and tungsten wires. Strictly speaking, the impact of these results on the practical development of polarization devices in HDB was zero [4], [28]. However, they were a very important step in the theory of gratings, on the one hand, and in the refining of the method of semi-inversion (or method of analytical regularization), on the other hand. This allows one to rate this work as a milestone itself for the research into computational electromagnetics in the IRE and the Soviet Union.

Figure 6. *1968. Lev Vainshtein lectures in the Kharkov State University on a visit. Sitting from left to right in front of him are Shestopalov, Tereshchenko (dean of radio physics faculty), and Kuleshov.*

Working on polarization QO devices, researchers kept in mind that they could use HDB-20 in the whole range of $\lambda = 0.5$ to 0.8 mm. Among new components, there were the following: double-lens transformers, Fabry-Perot wavemeter with metal-strip (1-μm-thick silver or aluminum) grating reflectors made by vacuum infusion on the quartz substrate, phase shifters with dihedral reflectors in the 90° angled bends of the beamguide, and so on. However, the main focus was on devices using the tungsten wire grids of $2b = 10\ \mu$m, $l = 20$ to 60 μm fixed in the frame of $D = 40$ mm. Yanovski was a leader in this work. Resulted polarization devices were attenuators consisting of three polarizers with single and double grids inclined to the beamguide axis, cassette beam splitters based on wire grids, phase shifters having grids backed with plane metal mirrors, and other units [28]. The developed measuring devices were a complete kit for λ = 0.5–0.8 mm (Figure 7) and could be used with longer waves up to λ = 1.7 mm. The experimental shop produced over 900 separate components in 1966–1971, and the pilot factory attached to IRE released 40 full kits of the QO measuring circuits to equip 20 industries and laboratories in the next two years.

From a Classified Patent to the Microwave Pioneer Award

The time of patenting the HDB came only in 1969. In part, this was a consequence of secrecy around the QO circuits. Besides, before that moment, the HDB components were only an innovative technology without immediate application. In 1969, the new Tokamak program was approved in IAE, aimed at the really large fusion machines. For new-generation Tokamaks, IAE scientists needed submillimeter-wave diagnostic systems and naturally turned to Kuleshov's beamguides. Perhaps this added to the motivation of designers a desire to protect their priority. In the Soviet Union, all patents were submitted to and judged by the special Institute of State Patent Examination in Moscow. When applying for a patent, they had first to prove the novelty of HDB. This was easy, as eventual design of HDB with its rigid metal tube encasing a dielectric tube, especially if ribbed, was different enough from the simplified geometry studied in [19]. Second, the designers had to decide about the list of authors. They remembered that paper-tube-encased lens beamguide of Akhiyezer, although completely different, was the closest to HDB of the known ones. Therefore, they invited Akhiyezer to join the list of authors when finally submitting a patent application in 1969. Here, according to the USSR practice, the authors were listed in alphabetical order. Therefore, the name of Akhiyezer appeared on the top of the list, although he had never been directly involved into the development of HDB.

The patent authored by Akhiyezer, Goroshko, Knyazkov, Kuleshov, Litvinov, Tolmachev, Shcherbov, and Yanovski was entitled, "Dielectric beamguide of the sub-mm wavelength range" (see Figure 8). It was approved in 1971 with a date of priority of November 28, 1969 (declassified in 1972) [35]. The subject of invention was formulated as follows:

1) Dielectric waveguide of the submillimeter-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 the 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 off of the spurious modes, the inner surface of the dielectric tube [see beamguide from 1)] is provided with longitudinal triangular ribs having the step smaller than half-wavelength.

As explained, publishing papers about HDB in open technical journals had not been always easy, and the authors frequently resorted to closed publications. For example, a paper [36] on the measuring technique, where HDB was only mentioned, was published in a classified technical journal. Finally, in 1972, young engineer Anatoly Goroshko was working toward his Ph.D. degree, with Kuleshov as supervisor, made a series of thorough measurements of the wave propagation in HDB. This suggested writing a paper. Fortunately there was a small-circulation journal *Radiotekhnika* aperiodically published at the Kharkov State (now National) University and known only inside the Soviet Union to a limited number of experts. Here, instead of presenting a study of electromagnetic characteristics of HDB itself, the authors organized the paper as a verification of the limits of validity of a particular formula of [19] concerning the attenuation of the principal mode in HDB. This happened to be the first open-literature publication on HDB [37]. However, sending a paper to an international periodical, although formally possible, was considered at that time useless and even risky. A similar situation existed around new QO circuit components. For example, by the end of the "Oliva" project, Kuleshov and his team held 24 USSR patents; however, the first brief publication on these devices was only in 1974 in a conference proceedings [38].

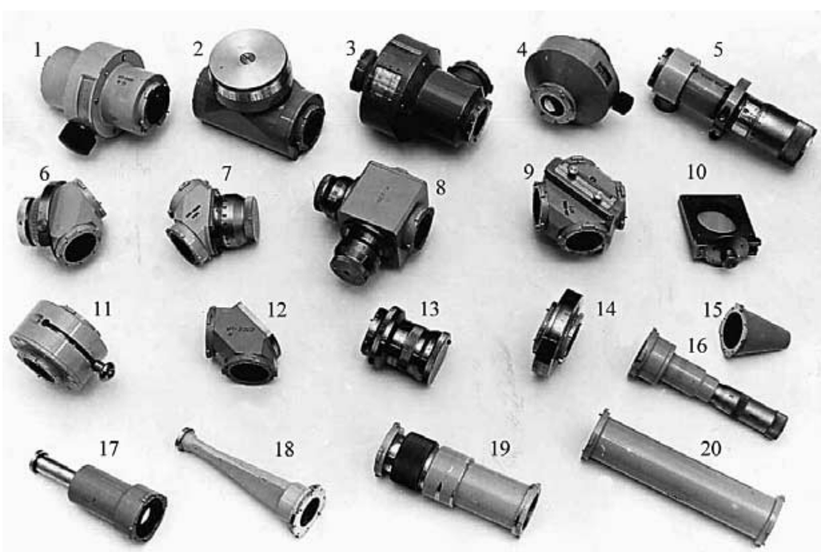

Figure 7. *1971. LEGO-like kit for submillimeter wave engineer. HDB-based components and devices for the λ= 0.8–1.5 mm developed by the end of the "Oliva" project and later used for building the* Tokamak *plasma interferometers. 1) polarization attenuator, 2) polarization phase shifter, 3) tunable attenuator and power divider, 4) polarization plane rotator, 5) wave meter, 6) polarization transformer, 7) tunable phase shifter, 8) matching unit, 9) beam splitter, 10) cassette of polarization discriminator, 11) linear polarizer, 12) right-angled bend, 13) movable two-facet reflector, 14) rotary joint, 15) termination load, 16) movable reflector, 17) and 18) two waveguide-to-beamguide transformers, 19) telescopic section, and 20) straight section.*

The 1972 National Prize deserves some comments. As it is visible from studying the technical reports, the major breakthrough was "Ozero," with a kit of some 20 innovative QO components. However, by the time of its completion, the end of 1966, the HDB technology yet had no applications. This absence of immediate customers even caused an almost two-year break in direct funding. "Oliva" had a narrower scope around the principle of polarization discrimination and therefore a comparatively smaller impact. However, by the time of its completion, at the end of 1971, the IRE team of QO designers had been working again in extremely close collaboration with the Tokamak scientists of IAE. This was a crucial circumstance, as it provided evidence of application potentials of HDB and guaranteed powerful support in any competition. At first, then IRE director academician A. Usikov encouraged Kuleshov to submit the results of two projects for a Prize by NASU. When the nomination was discussed at a meeting of the IRE Scientific Board, a suggestion came to apply also for a National Prize from the Ukraine. The nomination was sent to Kiev, where the Prize Committee had to make up a decision.

One hidden point of this story is very interesting: Kuleshov had never been a member of the Communist Party (CP), which was a huge drawback from the viewpoint of the district, city, and republic CP committees who all had to examine the prize nomination. Nevertheless, he won. When asked about such curious good luck, Kuleshov says that it was his previous title of the 1960 Lenin Prize awardee that made him free of the political pressure. Unlike the majority of his colleagues, for years he used to decline invitations to join the CP, saying that "he was not yet good enough." The roots of this attitude were in his student memories of 1940. Once, at the time of annual university examinations, he was assigned to participate in some political action of young communists that had spoiled his grades; however, it worked as preventive vaccination.


СОЮЗ СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

КОМИТЕТ ПО ДЕЛАМ ИЗОБРЕТЕНИЙ И ОТКРЫТИЙ при СОВЕТЕ МИНИСТРОВ СССР

АВТОРСКОЕ СВИДЕТЕЛЬСТВО

№ 302064

На основании полномочий, предоставленных Правительством СССР, Комитет по делам изобретений и открытий при Совете Министров СССР выдал настоящее свидетельство

КУЛЕШОВУ Евгению Митрофановичу
и другим, указанным в прилагаемом описании

на изобретение "Диэлектрический лучевод субмиллиметрового диапазона волн"

по заявке № 1380503 с приоритетом от 28 ноября 1969 г.
автор и изобретения: они же

Зарегистрировано в Государственном реестре изобретений Союза ССР

3 февраля 1971 г.

Действие авторского свидетельства распространяется на всю территорию Союза ССР

Председатель Комитета

Начальник отдела

Figure 8. *1972. Front page of the USSR Patent given to the inventors of HDB.*

In the end of 1972, for the research entitled, "Development and implementation of the radiometric system of millimeter and sub-millimeter wavelength ranges," the team consisting of Kuleshov, Yanovski, Litvinov, Scherbov, Knyazkov, Goroshko, Tsygankov, Masalov, and Shestopalov were awarded a National Prize from the Ukraine. The list had to be limited by nine names, however, because USSR ideology requested that scientists and engineers should always be cooperating with the working class; therefore, a brilliant metal worker A. Tsygankov was included. In addition to the QO practitioners, two of the four theorists who worked on the simulation of gratings were also on the award list. By a twist of fate, V. Sologub (1939–1987) was not included, although his contribution to that study was the strongest. Before the nomination was finalized, Sologub had applied for an individual Young Communist Prize of the USSR (never received), and therefore, his name was not on the team list. Kirilenko, a fresh Ph.D., was not considered at all because he was prohibitively young for a Prize. Next year, however, Sologub was among the authors of the book [34], and Kirilenko contributed his chapters on "venice-blind" and "echelett" gratings anonymously. By that moment, a dramatic change had already occurred in the IRE: by decision of the Kharkov CP Committee, Usikov was replaced at his post of director by Shestopalov. This explains the curious composition on the official photo reproduced in Figure 9. This team of practitioners and theorists never joined again in the follow-on projects.

Since the 1970s, the activities of the QO department were focused entirely on the development of HDB-based instruments and systems. Here, the major application area was hot plasma diagnostics in new large Tokamaks (Figure 1). Fortunately, they dwelled on the development of the measuring techniques including reflectometry and polarimetry since 1970 [36]. Other HDB-based systems elaborated in IRE included radars in the 1970–1980s and RCS testing ranges in the 1990s. These ranges were of two types. One was designed

Figure. 9. *1973. A newspaper photo of the National Prize awardees (left to right): Kuleshov, Tsygankov, Goroshko, Knyazkov (sitting), Scherbov, Masalov, Yanovski, Shestopalov (sitting), and Litvinov.*

for indoor measurements of backscattering from the scaled models of ships in a test pool, and the other for studying the scattering matrices of small objects placed inside HDB. Some information on these systems can be found in [39]–[41]. The story of the IEEE Microwave Pioneer Award, 2000 started in 1997, when the secretary of the recently organized IEEE MTT East Ukraine Joint Chapter in Kharkov received a routine suggestion to nominate members for annual MTT-S awards. The crucial role was played by the references written by three IEEE Fellows, H. Unger, K. Schuenemann, and K. Yasumoto (Figure 10), who visited Kharkov for the International Symposium on Mm and Sub-mm Waves (MSMW-98). They were guests of the QO department of IRE and could see the beamguides, RCS testing ranges, and other instruments. Still greater was the encouragement and support expressed by the Chairman of the MTT-S Awards Committee, P. Staeker. Unfortunately, Kuleshov failed to travel to Boston for the award ceremony at the IMS-2000. At his age, this is understandable. Instead he sent a videotape, which was displayed at the symposium. Besides, a full copy of the 1964 intermediate report of the project "Ozero" [20], formerly classified, was presented to the MTT-S as a token of the international nature of science and engineering.

A Lesson of History

When looking at the history of QO technology developments in the 1960–1970s, one can notice a competition between the Western and the Soviet Union research communities reflecting a more profound competition between two political and economic systems. To support its state science, the Soviet Union actively exploited the open character of fundamental research in the West (many useful insights of how it worked can be found in the stunning book [42]). The flows of information were quite efficient and multiple: from buying the periodicals to regular abstracting to publishing complete translated versions of key journals (e.g., *Proceedings of the IEEE*) and books. In parallel to general libraries, each USSR institute had a special library for classified literature, including translations. However, it is well known that these measures were only shortening the lag but never eliminated it. In part, that was because the USSR scientists were not able to take part in the international forums and hence to update efficiently their R&D pattern. Normally emerged in the West, new ideas and principles were first discussed at the conferences and published next year, like OSW, lens line, and so on. In contrast, experimental and engineering innovations in microwaves were discouraged and even prohibited from open publication in the Soviet Union. The work on the advanced lens beamguide [16] was published only four years after a classified USSR patent was given. A paper on reflector beamguide was published early in an USSR journal [17] thanks to purely theoretical consideration as compared with the measurements presented in *IEEE Transactions on Microwave Theory and Techniques* [18] and elsewhere. Kuleshov's finding of HDB was done, as explained above, by a team of practitioners. This was a rare example of truly USSR-born microwave technology. However, it forever remained endemic of USSR development, as it published too little to attract attention in the West.

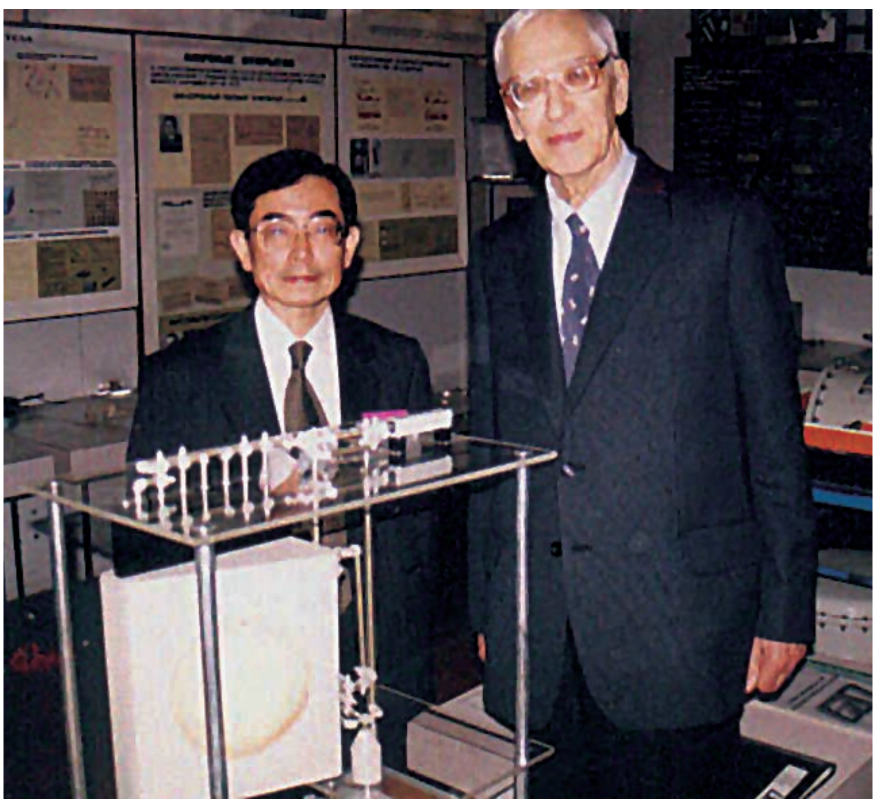

Figure 10. *2001. Professor K. Yasumoto and Kuleshov near a model of* Tokamak *interferometer in IRE.*

The IRE-Kharkov team was lucky to have an exceptionally generous customer, the Tokamak department of IAE, whose funds were virtually unlimited within some 40 years before 1992. All that time, Tokamaks were equipped with multichannel interferometers built of components made either in IRE or, later, by the industry that used IRE's designs. From 1973 on, these components were based on HDB. Although before that Kuleshov had no direct funding of QO works from IAE, he had other projects from IAE related to earlier-type interferometers that helped him keep stability of the team and even make small pilot studies. In the West, Tokamak plasma diagnostics has followed a parallel road using the Gaussian-beam circuitry [8], [9], in part because HDB was not internationally known. (However, in the early 1990s, two small Tokamaks were bought from IAE by Kadhafi in Libya and by Iran's ayatollahs, equipped with single-channel 2-mm standard waveguide interferometers originally designed by Kuleshov in the 1960s.)

Collaboration with Tokamak science had much merit for IRE, whose first buildings and workshops were built in 1959 by using IAE's funding. However, it entailed unnecessary secrecy even around fundamental R&D. As a result, HDB was very slowly finding other areas of application, and mainly defense related. Besides, such outstanding implementation seemed to satisfy the HDB designers, who did not bother about publications. Now one can see that eventually the main victim was a fair recognition of the achievements of Kuleshov and his team out of the Soviet Union. Even though some papers around HDB and associated systems started appearing in the international journals in the 1990s, Western reviews on quasioptics and terahertz technologies [8], [9] never mentioned them and stated that such a structure was used only in waveguide lasers. This unlucky situation started changing only in 2000, when Kuleshov was awarded the Microwave Pioneer Award of the IEEE MTT Society. We hope that our article, in line with the previous publication [43], will contribute to proper positioning of his remarkable engineering accomplishment.

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References

[1] IRE Department of QO (2003) [Online]. Available: http://www.ire.kharkov.ua/depquasi

[2] A.A. Kostenko, A.I. Nosich, and I.A. Tishchenko, "Development of the first Soviet 3-coordinate *L*-band pulsed radar in Kharkov before WWII," *IEEE Antennas Propagat. Mag.*, vol. 44, pp. 28–49, Mar. 2001.

[3] Y.M. Kuleshov, "Measurements in the sub-mm band," in *Electronics and Radio Physics of Mm and Sub-mm Waves*, A.Y. Usikov, Ed. Kiev: Naukova Dumka Publ., 1986, pp. 140–157 (in Russian).

[4] Interviews of Y.M. Kuleshov and M.S. Yanovski, 2001–2002.

[5] A.A. Kostenko, "Quasioptics: historical background and modern trends," (in Russian), *Radiofizika i Radioastronomiya*, vol. 5. Kharkov: IRA Press, 2000, pp. 221–256.

[6] J.F. Ramsey, "Microwave antenna and waveguide techniques before 1900," *Proc. IRE*, vol. 46, no 2, pp. 405–415, 1958.

[7] B.Z. Katsenelenbaum, "Quasioptical methods of shaping and transmission of mm waves," (in Russian), *Uspekhi Fizicheskikh Nauk*, vol. 83, no. 1, pp. 81–105, 1964.

[8] P.F. Goldsmith, *Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications.* Piscataway, NJ: IEEE Press, 1998.

[9] P.H. Siegel, "Terahertz technology," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 910–928, Mar. 2002.

[10] E. Karplus, "Communication with quasioptical waves," *Proc. IRE*, vol. 19, pp. 1715–1730, 1931.

[11] L. Felsen, "Quasi-optical methods in diffraction theory," in *Proc. Symp. Quasi-Optics*, New York, 1964.

[12] B. Katsenelenbaum and V. Shevchenko, Eds. and Trans., *Kvazioptika*, (in Russian). Moscow: Mir, 1966.

[13] R.A. Valitov, Ed., *Sub-mm Wave Technologies,* (in Russian). Moscow: Sovetskoye Radio, 1969.

[14] G. Goubau and F. Schwering, "On the guided wave propagation of electromagnetic wave beams," *IEEE Trans. Microwave Theory Tech.*, vol. 9, pp. 248–256, Mar. 1961.

[15] J.E. Christian and G. Goubau, "Some measurements on an iris beam waveguide," *Proc. IEEE*, vol. 49, pp. 1679–1680, Nov. 1961.

[16] V.V. Shevchenko, "Optical transmission line for mm and sub-mm waves," USSR Patent 171453, Sept. 2, 1963.

[17] B.Z. Katsenelenbaum, "Transmission of mm waves by reflection from a series of focusing reflectors," *Radio Eng. Electron Phys.*, no. 9, p. 1446, 1963.

[18] J.E. Degenford, M.D. Sirkis, and W.H. Steier, "The reflecting beam waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 12, pp. 445–453, Jul. 1964.

[19] E.A. Marcatili and R.A. Schmeltzer, "Hollow metallic and dielectric waveguides for long distance optical transmission and lasers," *Bell Syst. Tech. J.*, vol. 43, no. 4, pp. 1783–1809, 1964.

[20] Y.M. Kuleshov, "Exploration of opportunities of development of radiomeasuring equipment and devices in the sub-mm band based on quasi-optical principles," (in Russian), Technical Report "Ozero," Kharkov, IRE, 1964 (intermediate) and 1966 (final).

[21] A.Y. Usikov, "Development of radiomeasuring equipment in the 4-mm band," (in Russian), Technical Report "Zhimolost," Kharkov, IRE, 1955.

[22] Y.M. Kuleshov, "Development of design methods for wideband measuring equipment in the mm band," (in Russian), Technical Report "Flyuger," Kharkov, IRE, 1957.

[23] Y.M. Kuleshov, "Development of radiomeasuring equipment kit in the 3-mm band," Technical Report "Duga," Kharkov, IRE, 1959 (in Russian).

[24] Y.M. Kuleshov, "Exploration of opportunities of development of radiomeasuring equipment in the 2-mm band," Technical Report "Roza," Kharkov, IRE, 1961 (in Russian).

[25] Y.M. Kuleshov, "Development of measuring equipment in the mm wavelength band for plasma investigation," (in Russian), Technical Report "Tema No. 9," Kharkov, IRE, 1958.

[26] Y.M. Kuleshov, "Development of measuring equipment and radio interferometers in the 1-2 mm band," (in Russian), Technical Report "Svet," Kharkov, IRE, 1964.

[27] A.N. Akhiyezer, "Investigation of devices in quasioptical beams," (in Russian), Trudy Metrologicheskikh Institutov, Moscow, USSR Standard Committee Publication 99 (159), 1969.

[28] Y.M. Kuleshov, "Exploration of opportunities of development of a kit of radiomeasuring equipment in the sub-mm band," (in Russian), Technical Report "Oliva," Kharkov, IRE, 1971.

[29] N.A. Irisova, "Sub-mm wave metrics" (in Russian), *Vestnik AN SSSR*, no. 10, pp. 63–71, 1968.

[30] L.A. Vainshtein, "Electrodynamic theory of gratings," (in Russian), in *Elektronika Bolshikh Moshchnostei*, no. 2. Moscow: Nauka, 1963, pp. 26–74.

[31] E.A. Lewis and J.P. Casey, "Electromagnetic reflection and transmission by gratings of resistive wires," *J. Appl. Phys.*, vol. 23, pp. 603–608, 1952.

[32] J.R. Wait, "Reflection at arbitrary incidence from a parallel wire grid," *Appl. Sci. Res. B*, vol. 4, pp. 393–400, 1954.

[33] V. Twersky, "On scattering of waves by infinite grating of circular cylinders," *IRE Trans. Antennas Propagat.*, vol. 10, no. 6, pp. 757–765, 1962.

[34] V.P. Shestopalov, L.N. Litvinenko, S.A. Masalov, and V.G. Sologub, *Diffraction of Waves by Gratings,* (in Russian). Kharkov: Kharkov State Univ. Press, 1973.

[35] A.N. Akhiyezer, A.I. Goroshko, B.N. Knyazkov, Y.M. Kuleshov, D.D. Litvinov, N.I. Tolmachev, V.A. Shcherbov, and M.S. Yanovski, "Dielectric beamguide of sub-mm wavelength range," USSR Patent 302054 CCCP, Nov. 28, 1969.

[36] V.A. Shcherbov, Y.M. Kuleshov, and A.I. Goroshko, "Setup for measuring the amplitude, phase and polarization characteristics in the sub-mm range," (in Russian), *Voprosy Radioelektroniki*, pt. 4, no. 9, pp. 38–44, 1970.

[37] A.I. Goroshko and Y.M. Kuleshov, "Investigation of a hollow dielectric beamguide of the mm and sub-mm wavelength ranges," (in Russian), *Radiotekhnika*, vol. 21. Kharkov: Kharkov State Univ. Press, 1972, pp. 215–219.

[38] Y.M. Kuleshov et al., "Quasioptical measuring devices for mm and sub-mm waves," (in Russian), in *Proc. USSR Symp. Propagation on Mm and Sub-mm Waves in Atmosphere*, Moscow, Russia, 1974, pp. 124–127.

[39] Y.E. Kamenev et al., "Sub-mm laser interferometer for high density plasma diagnostics," *Int. J. Infrared Mm Waves*, vol. 16, no. 6, pp. 999–1007, 1995.

[40] V.I. Bezborodov, A.A. Kostenko, G.I. Khlopov, and M.S. Yanovski, "Quasioptical antenna duplexers," *Int. J. Infrared Mm Waves*, vol. 18, no. 7, pp. 1411–1422, 1997.

[41] V.K. Kiseliov, T.M. Kushta, and P.K. Nesterov, "Quasioptical waveguide modeling method and micro-compact range for the mm and sub-mm wave bands," *IEEE Trans. Antennas Propagat.*, vol. 49, pp. 784–792, May 2001.

[42] P. Kneen, *Soviet Scientists and the State*. Albany: State Univ. New York Press, 1984.

[43] A.I. Nosich, Y.M. Poplavko, D.M. Vavriv, and F.J. Yanovsky, Microwaves in Ukraine," *IEEE Microwave*, vol. 2, pp. 82–90, April 2002.