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Quasi-Optics of Near-MM and Sub-MM Waves in IRE-Kharkov, Ukraine in the 1960-70's

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The paper presents a retrospective review of the development of short millimeter (mm) and sub-mm wavelength quasi-optical technology based on the hollow dielectric beamguide as a transmission line. This development started in 1964 and was widely used in the nuclear fusion research in USSR. Later on the same principles were applied in the development of battlefield radars and microcompact RCS measurement ranges.

INTRODUCTION

In June 2000, Yevgeny M. Kuleshov, an Ukrainian scientist, was awarded an IEEE MTT Society Microwave Pioneer Award for the development, in 1964-1972, of a hollow dielectric beamguide (HDB) technology and measuring circuits of the near-mm and sub-mm wavelength ranges (1). This certifies an outstanding and recognized contribution of Kuleshov and his team to this area of engineering science made more than 30 years before today's interest in terahertz range. However, an invited paper by Sorrentino et al. (2) on microwaves in Europe, in the jubilee issue of the *IEEE Transactions on MTT*, does not mention, paradoxically, Ukraine at all. That is why, although HDB technology had been highlighted in Soviet papers like Kuleshov (3), we believe that our retrospective review can be of interest for the European microwave community.

PRINCIPAL DEVELOPMENTS

The quasi-optics department (QOD) exists in IRE NASU (a.k.a. IRE-Kharkov, http://www.ire.kharkov.ua) since its establishment in 1955. Headed by Kuleshov, by the early-1960's QOD had already accumulated much experience in the design of radiometric devices based on conventional hollow waveguides. The smallest waveguide they used had the cross-section of 1.1×0.55 mm^2 ($\lambda = 1.15$ - 1.7 mm). This enabled one to perform all types of measurements through the whole mm-wave range, the main area of application being remote diagnostics of hot plasma in the first Tokamak fusion machines (see below). However, soon it was realized that a single-mode waveguide could not be used as a basic transmission line of the near mm waves due to the increased losses and critical tolerances. At that time, QO methods of transmission and conversion of electromagnetic waves had already attracted attention, and Kuleshov turned to them. It should be emphasized that he started developing QO sub-mm range circuitry five years before a real need in such a wavelength range emerged at his well-funded Tokamak customers. It is no mistake to say that by so doing he demonstrated a bright foresight of the progress of microwave science and engineering.

Fig. 1 Sections of HDB of 40 and 20-mm diameter, and dielectric tubes of smooth and ribbed inner surface (1964).

Research project "Ozero". Official beginning of research on QO in IRE dates 1964 when the first phase of a pioneering R&D project "Ozero" was completed for the Ministry of Radio Industry. The proposition came from Kuleshov, preceded by numerous discussions, tests, and pilot experiments around the type of transmission line and separate components. The goal of the work was to verify a possibility of developing a kit of general-purpose devices based on a QO beamguide in the wavelength range of 0.7 to 1.7 mm. The whole project was performed in 1964-1966. At the first stage, the team developed the concept of HDB in the form of a slightly lossy dielectric tube inserted into another, metal tube serving as a support structure, which provided rigidity and completely eliminated the field leakage (Fig. 1). In the beginning of

1965, an important paper authored by Marcatilli and Schmeltzer (4) reached the library of IRE. In this paper, they analyzed theoretically the modes in a large-diameter circular channel in an unbounded dielectric medium. The principal hybrid HE_{11} mode having minimum attenuation was considered in detail and suggested as a candidate for the long-range transmission of the optical power. This confirmed the correctness of the choice of HDB as a basic line and also enabled the IRE developers to obtain an insight into its possible characteristics. A beamguide encased into a protective rigid metal tube was patented by Akhiezer et al. (5) in 1969 but disclosed only in 1992. Two type HDBs with the inner diameters of 40 mm (for $\lambda = 1.5 - 3$ mm) and 20 mm (for $\lambda = 0.7 - 1.7$ mm) were developed. In both cases a tube 5-mm thick made of phenoplast with sections 60 mm each was used. It was inserted into a section of metal tube of the required size (25 mm to 1000 mm). There were two designs of the dielectric sections: with a smooth inner wall and with longitudinal ribs of triangular cross-section. The sections were joined together with ring flange junctions. Goroshko and Kuleshov (6) published experimental study of mode attenuation and field pattern in the beamguide cross section in open literature only in 1972, as a student work in a low-circulation university digest. The reason was that all Soviet fusion-related R&D were heavily classified till 1992. E.g., the first technical report of "Ozero" (1964, classified till 1999) already presented full design documentation on HDB, results of experiments, and a kit of radiometric devices and components based on HDB. Among them were waveguide-to-beamguide transformers, beamguide tapers, wavemeters, attenuators, phase shifters, beam splitters, termination and movable loads, movable ref-lectors, reflector matchers, corner transition, rotary junctions, telescopic junctions, thermistor heads, calorimeters, etc. Moreover, there were even pilot intereferometric devices for studying the amplitude and phase characteristics of electromagnetic field at the output of QO circuits, and both direct-reading and interferometric QO reflectivity meters. Needless to say that fundamental design principles of the above-mentioned QO devices and systems were well known. In fact, they were verified as early as in the end of the 19^{th} century, and in the 1950's they were widely used in open-type (Gaussian-beam) QO devices. However, their implementation in HDB by Kuleshov (Fig. 2) was remarkable due to detail analysis of electromagnetic performance, original combination of elements and units in complicated systems, and non-conventional design approaches in developing many specific units employed later in numerous measuring devices.

Research project "Oliva". From the viewpoint of a further perfection of sub-mm wave devices and a wider

Fig. 2. Yevgeny Kuleshov in 1960.

implementation of the polarization principles, the project "Oliva" (1968-1971) was of great importance. It was a logical extension of "Ozero" and performed by QOD for the same customer. It demonstrated that in the range of $\lambda = 0.5 - 0.8$ mm all the devices could be based on one 20-mm diameter HDB. This simplified essentially the design of components and reduced their dimensions and weight. The main attention was paid to the development of polarization devices with small-period diffraction gratings made of tungsten wires. As a result, measuring polarization attenuators, cassette-type polarization beam splitters, measuring polarization phase shifters, and matching transformers had been suggested and designed (Fig. 3). The requirements of "Oliva" were completely satisfied. The developed HDB-based devices composed a kit of wideband general-purpose building blocks used for the measurements with $\lambda = 0.5 - 0.8$ mm. Moreover, technical characteristics and performance of the QO devices surpassed their waveguide analogues of the microwave range, and tests had proven that they could be used at longer wavelengths up to λ=1.7 mm. In 1970, the pilot shop of IRE launched a small-series production of the kits of QO measuring devices. Having no analogues in the mm and sub-mm wave ranges, these devices were widely used in the Soviet scientific experiments and new technologies. The serial production of the kits lasted till 1980, when it was transferred to a Vilnius industry, with more than 1000 kits supplied to 40 different customers. In 1972, the IRE team was awarded a National Prize of Ukraine, for the development and implementation of a complex of mm and sub-mm wave radiometric devices. Further work of QOD, along with R&D on the devices based on new methods of microwave power transmission and promising design principles, was aimed at finding new application areas of the HDB technology in various defense and scientific systems.

FURTHER RESEARCH ON QUASI-OPTICS

New QO devices. Accumulation of expertise led the department to initiation of the work aimed at developing new promising QO devices. It was concentrated on wide-band isolators required in many physical experiments. In particular, they had designed an original isolator with a semiconductor reflector made of *n*-InSb for λ=0.65–1mm and the temperature of 77 ?. It was based on HDB, and so did QO ferrite devices (isolator and 3-port circulator) that used the Faraday effect in a longitudinally magnetiz-ed sample. To test a possible alternative to HDB and reduce the losses, the researchers used also a metal-dielectric waveguide (MDW) suggested in 1969 in IRE-Moscow by Vershinina et al (7). Fortunately, technical design solutions found in IRE for HDB were perfectly compatible with the concept of MDW as well. Particularly, the use of a circular MDW of the 20-mm diameter, whose internal wall was coated with a 0.2-mm thick fluoroplast layer, allowed avoiding time and effort-consuming redesigning. Square-section MDWs ($14\times14\,\mathrm{mm}^2$ for λ=1.15–3 mm and $10\times10\,\mathrm{mm}^2$ for λ=0.7–1.7mm) had also served as a basis for developing a complete kit of QO components for building radiometric circuits of the near-mm and sub-mm wave ranges.

Fig. 3. Quasi-optical "LEGO" kit for a sub-mm wave engineer (1971).
HDB-based components used for building wideband (λ=0.5-1.7 mm) measuring circuits:
Left to right from top to bottom: polarization attenuator, polarization phase shifter, tunable attenuator - power divider, polarization plane rotator, wave meter, polarization transformer, tunable phase shifter, matching unit, beam splitter, a cassette of polarization discriminator, linear polarizer, right-angled bend, movable two-facet reflector, rotary joint, termination load, movable reflector, two waveguide-to-beamguide transformers, telescopic section, straight section

Interferometers for plasma diagnostics. The work on hot plasma diagnostics systems for nuclear fusion R&D played a crucial role not only for QOD but also for IRE as a whole. In the late 1950's, nuclear-fusion program in the USSR was one of the highest priorities in science and technology. It was given all possible support: new R&D centers, virtually unlimited funding, aid of industry, etc., all supervised at the highest level. In 1958, Committee on Atomic Energy granted huge funds for the capital invest-ment in IRE to start the first project on the development of an interferometer for measuring the plasma in the first Tokamak of the Institute of Atomic Energy (IAE) in Moscow. Thanks to that, pilot production shops equipped with the best-available machines were put into operation soon, and construction of laboratory building was started. Initially, the IAE-sponsored projects (1958-1966) were focused on the development of hollow-waveguide measuring interferometers for $\lambda = 4 \div 2$ mm. They were used in small Tokamaks of the first generation, where the plasma camera had diameter 40 cm and electron plasma density was 7×10^{13} to 10^{14} cm $^{-3}$. In 1968, it was decided to build Tokamak-10 having a camera of doubled cross-section (80 cm), where the maximum density could exceed 2×10^{14}cm $^{-3}$. For the plasma diagnostics in this machine, a 9-channel interferometer was developed by combined efforts of IRE and IAE, with operating wavelength λ= 0.9 mm, Bagdasarov et al. (8). The circuit was based on HDB and reached dozens of meters in length. This system provided a tomography of plasma column and led to many exciting discoveries. Further versions of this system worked with λ=0.337, 0.195 and 0.119 mm (Fig. 4). Besides of IAE, QOD of IRE had designed plasma diagnostics systems for the Kharkov and Sukhumi Institutes of Physics and Technology. In the 1990's, 2-mm band single-channel waveguide interferometers were supplied to Hungary, Libya, and Iran together with small research Tokamaks built by IAE.

Radar systems. By the late 1960's, successful develop-ment of various mm-wave components based on HDB stimulated the work in IRE on QO radar antenna-feeding circuits. The work in this direction was associated with a series of research in the USSR aimed at designing the 2-mm band radars for the close-range battlefield operation. The corresponding projects were allocated by various institutions affiliated to the Ministry of Defense Industry and Ministry of Radio Industry. These were complex investigations, with many R&D organizations involved. One of the major problems was the development of an

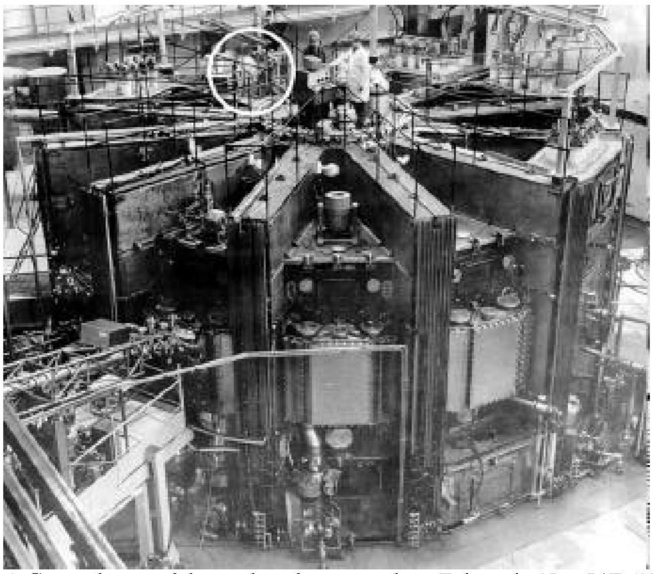

Fig. 4. General view of the nuclear fusion machine Tokamak-15 in IAE (1985).
A circle indicates the placement of QO multi-channel interferometer for plasma diagnostics with λ=0.195 mm.

efficient and compact receiving-transmitting device. Several types of QO transmission lines were considered. Here, IRE designed several modifications of radar systems on the basis of HDB. First of all, they built multifunctional receiving-transmitting systems for two-antenna radar stations that enabled to study 2-mm radar accuracy under various weather conditions and with various types of ground and vegetation. Further on, successful systems were built, which provided a simultaneous operation of receiver and transmitter with one common antenna and circularly polarized radiation, Knyazkov et. al. (9). MDWs of circular and square cross-sections were also studied as possible candidates for similar circuits.

Scientific instrument making. Devices built on HDB were used in measuring systems for various fundamental and applied researches. Namely, these were radiometers, ellipsometers, spectrometers, spectrum analyzers, thickness meters, and sensors of dielectrics and semiconductors. Completely new idea was analysis of the RCS characteristics of various objects by placing their downscaled models into HDB and measuring the forward and backward polarization scattering matrices of the mode HE_{11}. Based on this principle, Kiseliov et al. (10) designed a microcompact testing range for the near-mm and sub-mm wave bands. Now this application of HDB is the main one studied in IRE-Kharkov in view of complete halt of the Toka mak research in IAE.

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