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On the centenary of the discovery of submillimeter electromagnetic waves

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Contents

The paper examines some issues related to the history of the discovery of submillimeter electromagnetic waves. The results of M A Levitskaya's experiments are analyzed and compared with those of A A Glagoleva-Arkadieva's work in this field.

Keywords: submillimeter electromagnetic waves, mass emitters, resonators, spectra

1. Introduction

April 1, 2023 marks the 140th anniversary of the birth of Professor Maria Afanas'evna Levitskaya, one of the first women physicists in Russian and world science. M A Levitskaya was a graduate of St. Petersburg Higher Women's Courses (also known as Bestuzhev Courses after the name of the founder, K N Bestuzhev-Ryumin). On the recommendation of Professor Orest Danilovich Khvolson, M A Levitskaya spent her last two semesters (1905–1906) at the University of Berlin, specializing under the supervision of the greatest physicists of that time, Max Planck and Paul Drude. Then, from 1911 to 1914, she continued her education at the University of Göttingen under the supervision of Professor W Vioigt. After September 1923, she worked with Academician Abram Fedorovich Ioffe for ten years at the Leningrad State Physicotechnical X-Ray Institute [later, Leningrad Physicotechnical Institute (PTI)], and from 1934 to 1935 she worked with Academician Sergei Ivanovich Vavilov at the State Optical Institute (GOI). The last 28 years of her life, beginning August 1935, Maria Afanas'evna devoted to serving Voronezh State University.

The range of M A Levitskaya's scientific interests included problems concerning the generation and detection of ultrashort waves, X-ray studies of the strength of crystals and the structure of atomic nuclei, beta decay, diffusion in solids, X-ray spectroscopy of alloys and intermetallic compounds, and optical spectra of atoms and thin metal layers [1–20]. The result of her selfless work during the most difficult war years and at the completely destroyed post-war Voronezh University was the creation of the largest physical scientific school in the central black earth region of our country.

The greatest scientific significance was apparently M A Levitskaya's work in the field of submillimeter wave generation [1–8]. The results were reflected in classical physics textbooks [21, 22]. In particular, in [22, p. 494], we read, "Hertz's method of exciting electromagnetic waves using vibrator oscillations made it possible to obtain 1-m waves. Subsequently, many attempts were made to obtain waves of shorter wavelengths. In 1906, P N Lebedev, having made very miniature vibrators, generated 3-mm electromagnetic waves. Later (1924), M A Levitskaya obtained 0.2-mm waves... . Moscow University professors V K Arkadiev and A A Glagoleva-Arkadieva developed an original method of generating short electromagnetic waves using sparks between metal filings suspended in oil. They managed to obtain 0.1-mm waves... ."

The methods for generating and detecting short electromagnetic waves developed in [1, 23, 24] and the obtained fundamentally new results became an outstanding achievement of domestic and world science. The scientific success of M A Levitskaya and A A Glagoleva-Arkadieva, who gained worldwide fame, was highly appreciated by Academician S I Vavilov. In the monograph *Infrared Rays*, written at the request of S I Vavilov in 1934, M A Levitskaya summarized the results of her research and the most modern concepts in the field of the then emerging and practically very important infrared (IR) spectroscopy [8]. S I Vavilov was the editor-in-chief of the monograph, and M A Levitskaya was granted the degree of Doctor of Physical and Mathematical Sciences without defending a dissertation.

The year 2024 marks the centenary since the results on the successful generation of submillimeter waves in the range from 0.4 to 1.0 mm (0.8–0.3 THz) were published by M A Levitskaya and A A Glagoleva-Arkadieva. Until 1923,

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Служебн. отметки:

=СЕРДЕЧНО ПОЗДРАВЛЯЮ МАРИЮ АФАНАСЬЕВНУ 70-ЛЕТНИМ ЮБИЛЕЕМ ТЧК СОВЕТСКАЯ ФИЗИКА ОБЯЗАНА ВАШЕЙ САМООТВЕРЖЕННОЙ НАУЧНОЙ ДЕЯТЕЛЬНОСТИ ВАЖНЫМИ РЕЗУЛЬТАТАМИ ПЕРЕКРЫТИЕМ СПЕКТРА РЕШЕНИЕМ ПРОБЛЕМЫ ПРОЧНОСТИ ПЛАСТИЧНОСТИ ЗАКОНОМЕРНОСТЯМИ ЯДЕРНОЙ ФИЗИКИ ТЧК ЖЕЛАЮ МНОГИХ ЛЕТ УСПЕШНОЙ РАБОТЫ ОБЛАСТИ НАУКИ ВОСПИТАНИЯ КАДРОВ=АКАДЕМИК ИОФФЕ-

Photo 1. A F Ioffe's telegram to M A Levitskaya.

this part of the electromagnetic spectrum had not been characterized. The development of new methods of generation, spectroscopy, and detection of submillimeter waves not only was of fundamental importance at that time but also subsequently led to the active applied use of terahertz radiation (0.1–10 THz) in the development and creation of ultra-wideband data transmission channels with a speed of up to 100 Gb s^{-1}. Moreover, these methods are widely used in quality control systems for materials, pharmaceuticals, and security; in devices for detecting drugs and hidden objects; in biomedical applications, such as tomography and diagnostics of diseases; in earth and atmospheric sciences, including meteorology; in high-speed short-range communication systems; in space communication systems; etc. [25–33].

Recent years have seen the publication of reviews and monographs devoted to the problems of generation, detection, and control of radiation in the terahertz region of the electromagnetic wave scale, as well as to the history of their discovery. The diversity of opinions regarding the priority of the discovery of their central section — submillimeter waves (0.3–0.8 THz) — is noteworthy [25–27]. The majority of authors of modern textbooks, monographs, and review articles speak only of Professor Aleksandra Andreevna Glagoleva-Arkadieva from Moscow State University (MSU) as the discoverer of submillimeter waves [25, 26, 34], which contradicts [21, 22]. Unfortunately, the contribution of M A Levitskaya to the development of research in the field of submillimeter wave generation is not discussed in most modern books. In [26], the achievements of the two Russian women physicists in the field of submillimeter wave generation are not noted at all, and E Nichols and J Tear are named as the discoverers. In some papers, only H Rubens is considered the discoverer of submillimeter waves, who apparently made the most significant contribution to the development of radiation physics in the far-IR region, including the submillimeter region (100–400 μm), and to the elaboration of methods of its generation, spectroscopy, and detection [35–37].

We would like to draw the readers' attention to the fact that we have no doubts about the decisive contribution of A A Glagoleva-Arkadieva to the discovery of submillimeter waves. However, an answer is needed to the question about the role of M A Levitskaya in solving the problem of generating and studying the properties of submillimeter waves. Photo 1 shows A F Ioffe's telegram to M A Levitskaya, demonstrating recognition of the fundamental role of Maria Afanas'evna in the problem of generating submillimeter waves.

This paper is devoted to the history of the discovery of submillimeter electromagnetic waves and, in particular, to the consideration of the experiments performed by M A Levitskaya.

2. Analysis of state of the art of ultrashort wave generation by 1923

An active search for a solution to the problem of generating ultrashort electromagnetic waves began after H Hertz transformed an elementary oscillatory circuit in 1886, constructed a vibrator (hereinafter referred to as an *emitter*), and obtained waves 4.5–5.0 m in wavelength [38]. The emitter was an open oscillatory circuit consisting of two copper wires 5 mm thick with copper balls at one end, located at a distance of 7 mm from each other and connected to the secondary winding of a Ruhmkorff induction coil generating an induction current and a spark discharge (Fig. 1a). At the other ends of the wires were 30-cm-diameter hollow balls made of sheet metal zinc (they played the role of a capacitor C), the distance between which could be varied, thereby changing self-induction of the emitter without a significant change in its capacity. The generated electromagnetic waves were detected using the resonance method. The resonator was an open wire circuit (rectangular or round), in which a spark was generated when the emitter was excited under resonance conditions. In the first experiments, the distance between the hollow balls was about 1 m. Hertz found that the wavelength of the emitted waves was related to the length of the emitter by the relation $\lambda = 2l$ [38]. The generation of higher-frequency radiation was of fundamental importance for the experimental confirmation of J C Maxwell's theory, and the high importance of the problem was not questioned at that time.

Reducing the size of the emitter, which consisted of two metal cylinders 13 cm long and 3 cm in diameter with spherical roundings 4 mm in diameter and placed on the same axis with an interelectrode gap of 0.3 cm, made it possible to produce electromagnetic waves with a wavelength of $\lambda = 66$ cm (Fig. 1b) [38, 39]. The use of metal mirrors and an asphalt prism in experiments showed that the laws of refraction and reflection formulated in optics are fulfilled for the generated electromagnetic waves. Thus, H Hertz developed not only the ideology and technique of generating and detecting electromagnetic oscillations but also obtained evidence of the analogy between electromagnetic and light waves.

A Righi modified Hertz's emitter in 1894, using two balls fixed in ebonite plates as an emitter, the space between which was filled with oil. By exciting sparks in oil, he generated electromagnetic waves with $\lambda = 20$ cm (using balls with a diameter of 8 cm) (Fig. 1c, above) and with $\lambda = 2.6$ cm (using balls with a diameter of 0.8 cm) [39] (Fig. 1c, below).

Since one emitter provided relatively little power, methods for modifying its principle were developed. In 1890, O Lodge first proposed the principle of a mass emitter for generating electromagnetic waves (Fig. 1d) [40]. He used three or four identical nickel-plated spheres with a diameter of 121 cm on high insulating rods located at a certain distance from each other and enclosed between the spherical electrodes of the discharger.

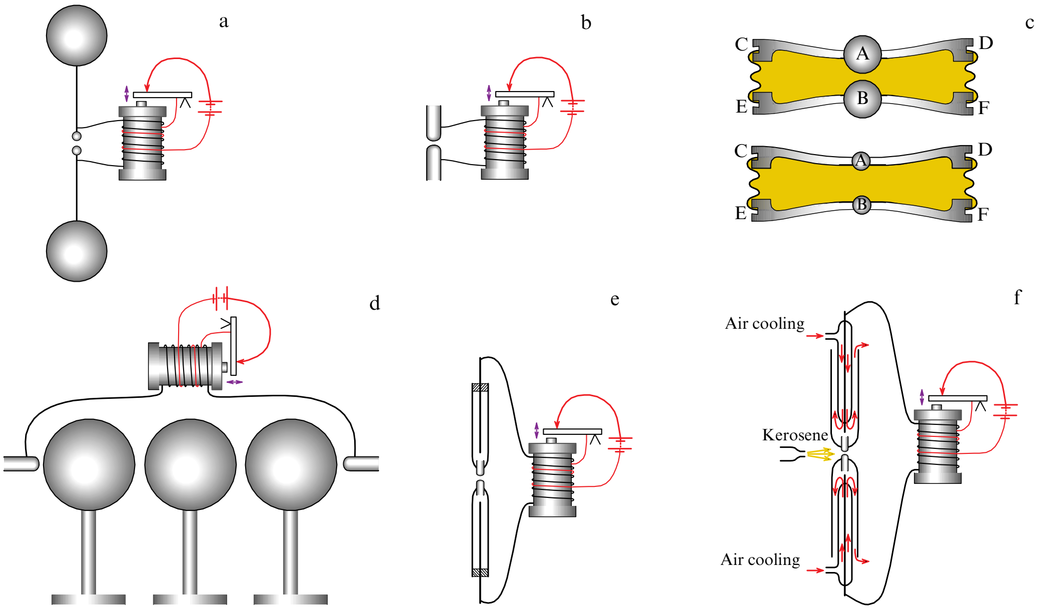

Figure 1. Schematic representation of emitters for generating electromagnetic waves: Hertz's emitter of (a) meter and (b) centimeter electromagnetic waves; (c) Righi's emitter; (d) O Lodge's mass emitter; (e) P N Lebedev's millimeter wavelength emitter; and (f) E Nichols and J Tear's cooled millimeter wave emitter.

In 1895, the founder of the first scientific physical school in Russia, Petr Nikolaevich Lebedev, using a miniature Hertz emitter with a total length of 2.6 mm, which consisted of two 0.5-mm-diameter and 1.3-mm-long platinum cylinders sealed in glass tubes, built into an oscillatory circuit, obtained millimeter-range radiation at wavelengths of 4 and 6 mm, and studied its properties (Fig. 1e) [41]. A thermoelement with two wire loops soldered to two halves of an open resonator connected to a galvanometer was used as a detector of these waves. Further miniaturization of the emitter turned out to be difficult, and P N Lebedev came to the conclusion that a new source was needed to generate waves shorter than 3 mm in wavelength [42, 43].

P N Lebedev's ideas were developed by his student Vladimir Konstantinovich Arkadiev — future corresponding member of the USSR Academy of Sciences, professor at Moscow State University, author of fundamental studies in the field of electromagnetism and the interaction of electromagnetic waves with matter [42]. He showed that, with a decrease in the size of the emitter, the dependence established by H Hertz does not work. Thus, an emitter 3 mm long made it possible to generate 11–13-mm waves. In 1914, V K Arkadiev used a generator with replaceable emitters to obtain ultrashort waves [43]. However, his research at that time did not lead to fundamental results in the field of generating submillimeter waves.

In 1920, W Möbius published the results of research that he begun in 1914 and devoted to solving two problems, i.e., analysis of the dispersion of millimeter waves (from 7 to 35 mm) in water and ethanol, and generation of waves with a wavelength of 4.0 to 0.3 mm [44]. Using spark excitation of an emitter similar to that proposed by P N Lebedev (Fig. 1e), which consisted of platinum rods enclosed in glass tubes in a 1–2-mm-long gap controlled by a micrometer screw, along with the fundamental oscillations, Möbius found a number of weak overtones with a wavelength shorter than 1 cm, down to 0.1 mm. The discovered electromagnetic oscillations were unstable and were attributed to high-order overtones of both the emitter and the resonator. However, these studies were not further developed.

In 1923, E Nichols and J Tear improved the Hertz emitter by using two tungsten cylinders with a diameter of 0.5 to 0.2 mm and a length of 5 to 0.2 mm, located at a distance of 0.1–0.2 mm from each other and sealed in glass (Fig. 1f) [45, 46]. The emitter was cooled by jets of compressed air (for auxiliary gaps) and kerosene (for the main gap). These experiments led to an expansion of the spectrum of the generated electromagnetic waves to a wavelength of 1.8 mm. At the same time, a weak overtone with $\lambda = 0.8$ mm was recorded [45]. Note that the studies by E Nichols and J Tear also confirmed the point of view of V K Arkadiev that, with a very small size of emitters, the wavelengths they emit during a spark discharge decrease more slowly than follows from the relationship derived by H Hertz [38]. However, the employed emitters were short-lived and deteriorated in a spark discharge. Thus, all efforts to generate electromagnetic waves by exciting them by radio-engineering means were limited by 1923 to a wavelength of 1.0–0.8 mm.

From the side of the far-IR region ("from the side of thermal rays"), H Rubens — German experimental physicist, outstanding optician, spectroscopist, and specialist in the physics of thermal radiation — conducted active research and achieved the greatest success in the development of principles of generation, filtration, and detection. He began his investigations in the field of IR spectroscopy at the end of the 19th century [48–50].

For spectral selection of radiation in the middle and far-IR ranges, H Rubens and E Nichols developed the residual ray method [48–50]. They installed a system of four-to-five reflecting surfaces of the material in question between the IR radiation source and the spectrometer slit. In the resonance region of eigenoscillations of the crystals under study, phonon frequencies of the corresponding materials were measured by reflection, and undesirable frequencies were gradually filtered out. Spectral analysis was performed using a diffraction grating. Later, H Rubens and H Hollnagel used

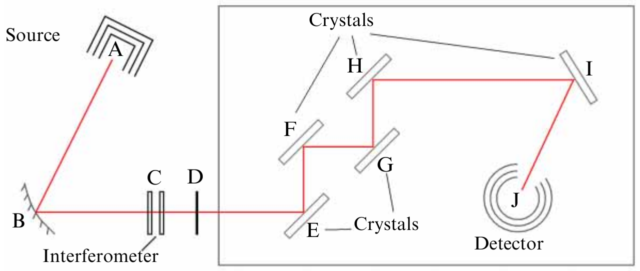

Figure 2. Schematic of residual ray method [48–50].

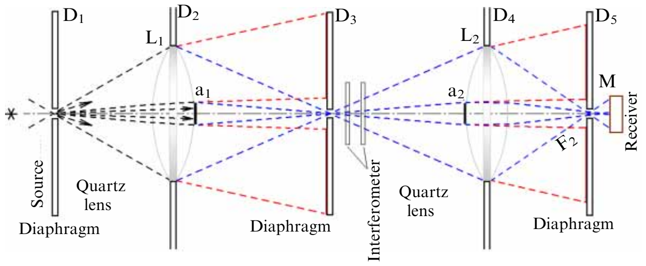

Figure 3. Schematic of 'quartz lens method' [54].

an interferometer to determine the spectral structure of residual radiation for some ionic crystals [51]. The setup of their experiments is shown in Fig. 2. Using the residual ray method, reflection was also found in the submillimeter region for some inorganic compounds (112.7 μm for AgBr and 117 μm for TlBr) [6]. The farthest (submillimeter) band of residual radiation was established by H Rubens and H Wartenberg in thallium iodide (TI) — 151.8 μm [52].

Of even greater importance for the development of research in the far-IR range was the invention of a new method of 'focal isolation' by H Rubens in collaboration with E Aschkinass [53]. The method was based on the use of anomalous dispersion of quartz, which manifests itself in a strong increase in its refractive index upon transition to the far-IR range in the region of $\lambda < 2.7$ μm ($n = 1.502 - 1.538$) and in the far-IR range, $\lambda > 60$ μm ($n = 2.14$), as well as in a significant increase in its absorption of radiation within the specified limits [8, 21, 53].

In the first experiments, long IR waves were selected using a quartz prism due to the large differences in the refractive indices of quartz. H Rubens and R Wood further developed this approach by using quartz lenses [54]. The optical scheme of the method is shown in Fig. 3. Within the framework of the 'quartz lens method,' use was made of the fact that quartz refracts long-wavelength radiation more strongly than short-wavelength radiation. Thus, using a quartz lens L_1, long-wavelength thermal waves were collected separately from short-wavelength ones (the focus of short-wavelength waves lay significantly further than the focus of long-wavelength waves). In addition, another lens L_2 was placed in the optical scheme so that the focus of long-wavelength waves produced a convergence point of rays F_2 on the receiver M. Diaphragms $D_2 - D_5$ retain short-wavelength radiation (Fig. 3). The remaining short-wavelength radiation near the main optical axis of the lens, passing without refraction, was eliminated by small screens a_1 and a_2 made of black paper.

The developed methods of spectral selection in the far-IR region led to significant results in the field of submillimeter wave generation. In 1911, H Rubens and O Bayer used the 'quartz lens method' with an interferometer to study in detail the emission spectrum of a quartz mercury arc lamp with an equivalent black body temperature of 4000 K down to 400 μm. Using an 8-mm-long mercury arc, they recorded two maxima with wavelengths of 218 μm and 343 μm using the interferometric technique [55–57].

In 1921, H Rubens used diffraction gratings to obtain the spectrum of a mercury quartz arc lamp. These gratings were a system of copper wires 1.004 mm (or 0.485 mm, 0.196 mm) thick, located at a distance of 2.0027 mm (or 0.9991 mm, 0.3997 mm, respectively). A system of maxima with wavelengths of 72.7 μm, 149.9 μm, 209.9 μm, and 324.8 μm and minima with wavelengths of 120.7 μm, 174.5 μm, and 267 μm was found [58]. The observed spectral pattern did not have a trivial interpretation. The first two maxima (72.7 μm and 149.9 μm) were attributed to thermal radiation of heated quartz, and the minimum at 120.7 μm was attributed to significant absorption of thermal radiation of hot quartz by water vapor. The long-wavelength bands were interpreted by H Rubens and O Baeyer as the rotation of molecules of two oppositely singly charged mercury ions (estimates yielded a value of 296 μm, while for molecules of doubly positively ionized and singly negatively ionized mercury ions this value was 209 μm) [55–57]. Further estimates of the rotational spectra of various configurations of diatomic mercury molecules also predicted the possibility of observing mercury vapor in the emission spectrum (412 μm, 685 μm) [59, 60].

Compared to the work of H Rubens, G Lasky, known for her studies of IR radiation, found in 1922 radiation with a wavelength of 400 μm while analyzing the properties and spectrum of a mercury-quartz lamp in an arc with the length reduced to 1 mm [61]. Note that when explaining the submillimeter section of the mercury lamp radiation spectrum, it was assumed that the bands with maxima at 209.9 μm and 324.8 μm belonged to the rotational spectrum of mercury hydride (HgH). Hydrogen was indeed detected in mercury vapor [62]. The presence of insignificant amounts of HgH in a mercury arc was confirmed by the results of experiments [63–65]. The moment of inertia of the HgH molecule was estimated by the method of successive extrapolation with the replacement of hydrogen by heavier atoms.

Thus, by the beginning of the 1920s, the submillimeter range was mastered by H Rubens, O Baeyer, and G Lasky from the far-IR range (thermal radiation), and radiation with wavelengths up to 0.4 mm (0.8 THz) was produced. From the side of the radio range, E Nichols and J Tear confidently generated electromagnetic waves with a wavelength of down to 1.0 mm (0.3 THz). The resulting 'empty' section (0.3–0.8 THz) fell on the central part of the terahertz range, extending from 0.1 to 10 THz (or 3.3 to 0.03-mm wavelengths). In width, this section is comparable to the visible part of the spectrum in the electromagnetic wave scale.

The problem of mastering this part of the spectrum was solved in Russia in parallel, albeit independently of each other, by M A Levitskaya and A A Glagoleva-Arkadieva.

3. Experiments of M A Levitskaya

M A Levitskaya started her research in the field of generation and detection of short and ultrashort electromagnetic waves during her internship at M Planck's laboratory (1905–1906). It should be noted that, at the same time, H Rubens also began his work at the University of Berlin. However, there is no evidence of communication or discussion of the problem of submillimeter waves between H Rubens and M A Levitskaya. The result of her internship with M Planck was her first scientific work devoted to the study of the attenuating secondary radiation of a rectilinear resonator irradiated in the region of short wavelengths (from 10 to 40 cm). M A Levitskaya completed these studies at the Physics Institute of St. Petersburg University in the period from 1908 to 1911 after she returned to Russia [66–68]. In these studies, she analyzed the attenuation decrement and showed that it is determined both by the radiation itself and by the release of Joule heat. Subsequently, such ideas were used in the detection of submillimeter waves. The obtained results were carefully discussed by the Russian physics community, were sharply criticized by P N Lebedev, and were voiced at a meeting of P S Ehrenfest's circle [69]. P S Ehrenfest's and A F Ioffe's attentive attitude to and M A Levitskaya's understanding of the problem in question, as well as the results achieved, contributed to the further development of her research.

M A Levitskaya independently began work on the development of a complex emitter for generating submillimeter waves at Tomsk University in 1918. Then, from August 1920 to September 1923, she continued this work at the Department of Experimental Physics at Central-Asia University in Tashkent. The first results demonstrating a successful attempt to shift from short electrical waves to long thermal waves were presented by M A Levitskaya on February 9, 1924 in *Physikalische Zeitschrift* [1]. In these experiments, she proposed an approach that differed from those used in previous studies of the problem of generating ultrashort waves.

First of all, the formulation of the problem being solved in [1] and its significance are of particular significance. The task was to develop a method for generating waves in the range of $10^{-2}-10^{-3}$ cm using purely electrical excitation or, conversely, achieving oscillations on the order of 10^{-1} cm using thermal sources [1]. Such an attempt was important for establishing the real continuity of the electromagnetic wave scale in this region. The importance of the problem to be solved was explained by the need to prove the possibility of "shifting from purely electrodynamic radiation of conductors to quantum radiation" [1]. The experiment presented below was set up and carried out by M A Levitskaya completely independently!

A source of short-wavelength electromagnetic waves was a 'mass emitter,' the general principle of which was formulated by O Lodge [40]. In M A Levitskaya's experiments, it represented an ordered system of small oscillators (lead balls 0.80–0.85 mm in diameter) located at the corners of a rectangular grid applied with diamond to a glass plate. The side of each square was 2 mm. The balls were glued to the glass using Canadian balsam. Between every two balls located horizontally, pieces of molybdenum wire 0.3 mm thick and about 0.5 mm long were also glued. The result was a grid consisting of 15 rows of balls with pieces of wire between them. Each row contained 25 balls. A schematic representation of a part of the mass emitter is shown in Fig. 4. Thus, an ordered system of mini-emitters was modeled. Nowadays, such ordered periodic model structures are called metamaterials and are used to obtain a medium with unusual dielectric parameters. M A Levitsky's mass emitter was apparently also one of the first examples of metamaterials. It was supposed to increase the radiation intensity by simultaneously exciting a regular system of elementary emitters by passing a spark discharge through maximally identical rows of emitters, the size of which varied within 5% [1].

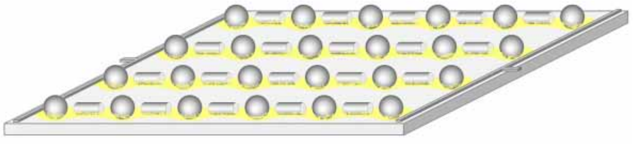

Figure 4. Schematic representation of M A Levitskaya's mass emitter used in [1].

The design of the mass emitter proposed in [1] was based on the work of J J Thomson [70]. According to [70], a conductive sphere excited at the ends of its diameter emits electrical oscillations for which the wavelengths of the fundamental oscillation and overtones are calculated as follows:

$$\begin{aligned} \lambda_0 &= \frac{4\pi a}{\sqrt{3}}\,, \\ \lambda_1 &= \frac{2\pi a}{1.8} = 0.48\lambda_0\,, \\ \lambda_2 &= \frac{2\pi a}{2.76} = 0.31\lambda_0\,, \\ \lambda_3 &= \frac{2\pi a}{3.98} = 0.217\lambda_0\,, \end{aligned}$$

where $2a$ is the diameter of the sphere. Thus, for each separately standing emitter, the expected values of the generated wavelengths of the fundamental oscillation and overtones are $\lambda_0 = 2.9$ mm, $\lambda_1 = 1.49$ mm, $\lambda_2 = 0.89$ mm, and $\lambda_3 = 0.62$ mm. The pieces of wire, according to estimates, should have produced harmonics with a wavelength of $\lambda_0 = 2.0$ mm, $\lambda_1 = 0.9$ mm, $\lambda_2 = 0.60$ mm, and $\lambda_3 = 0.41$ mm.

An estimate of the amount of energy emitted by the fundamental mode (see [1]) gave a value of less than half the energy of the fundamental oscillation (34%), which meant that it was possible to observe a noticeable intensity from higher harmonics from the region of thermal waves (66%).

Harmonics (overtones) were electrically excited by an inductor (a gap of 20 cm), a spark micrometer, the volume of six medium-sized Leyden jars, and a Tesla transformer. Voltage was applied using two brass strips. It was possible to excite simultaneously no more than five rows of the mass emitter.

The resonance method was used to detect the radiation of overtones of oscillations from the system of elementary emitters. Unlike the frame (open wire circuit) used by most researchers as a detector of electromagnetic waves, resonance ensured selectivity of their detection. The wavelength of the overtone radiation from the mass emitter should not be longer than 0.43 mm [1]. Therefore, to record the radiation of the mass generator, M A Levitskaya proposed an original resonator, which was a suspension of copper balls in a dielectric (in paraffin) that was maximally transparent in the far-IR region. The resonator was fabricated by spraying copper electrodes with liquid paraffin until a brown-black color was observed. The largest particles were precipitated in the resulting mass of paraffin with copper particles, when it was still liquid. After the paraffin solidified, the largest, 0.08–0.02 mm diameter, copper balls with a concentration of $350\ \mathrm{cm}^{-3}$ were in the upper layer.

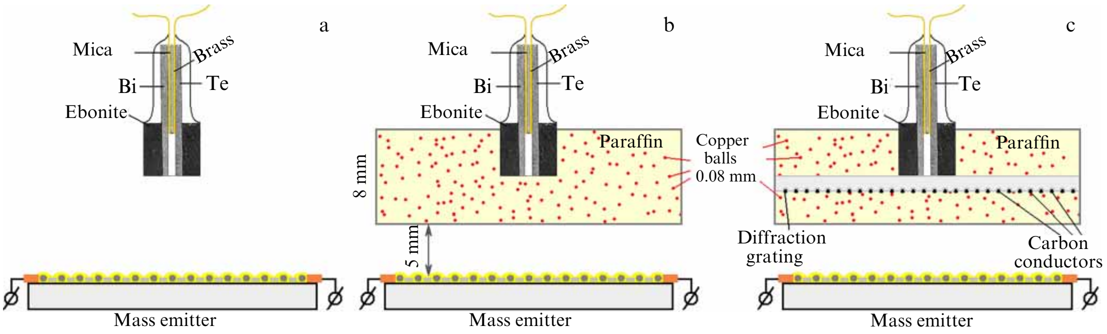

Figure 5. Diagram of M A Levitskaya's experiment for generating submillimeter waves: (a) mass generator, (b) resonator, and (c) resonator with a diffraction grating.

Because of resonance, part of the energy belonging to the higher harmonics of the mass emitter was expected to be absorbed by the balls in the resonator, to be converted into heat, and to heat the paraffin (which was presumably transparent in the studied region).

An increase in the layer temperature was measured by a special sensitive thermocouple made of Bi–Te alloy and connected to a galvanometer. The thermocouple, freely placed in the air in front of the operating mass emitter at a distance of 1–2 cm (Fig. 5a), showed the absence of a noticeable signal when the emitter was excited. A noticeable deviation on the galvanometer was observed when the thermocouple connected to it was immersed in molten paraffin at a distance of 3 mm from the outer surface of the resonator containing copper balls and facing the mass emitter (Fig. 5b). In this case, the resonator was covered with cotton wool for thermal insulation, and its front part (left open) was located at a distance of about 5 mm from the plane of the mass emitter (Fig. 5b).

To prove the wave nature of the radiation generated by the mass emitter, experiments were performed using a diffraction grating with conducting grooves. Note that the specific effect of wire gratings on the transmission of electromagnetic waves was discovered by H Hertz. The component of the electric field perpendicular to the wires was well transmitted by the grating, while the component of the electric field parallel to the wires was not. Similar features of the passage of 'heat rays' in the far-IR region through a diffraction grating were also discovered and studied by Du Bois and Rubens [71].

Despite very poor conditions for performing experiments in Tomsk and Tashkent and in the absence of a possibility of using a spectral device, M A Levitskaya exploited this feature of the diffraction grating. Use was made of a diffraction grating with a constant of 100 cm^{-1}, the surface of which was rubbed with graphite powder until grooves with electrical conductivity appeared. The width of the grooves was about $1/200$ mm. The resonating layer was melted, and the grating was immersed in paraffin until it touched the thermocouple (Fig. 5c). Then the layer was allowed to solidify again.

If we assume that the observed secondary radiation in the resonator is strictly temperature dependent, then a change in the position of the conducting grooves of the diffraction grating should not affect the amount of thermocouple-detected heat from the heated paraffin. Otherwise, during the propagation of polarized waves associated with overtones generated by the mass emitter, as well as those caused by re-radiation from the resonator balls, the position of the conducting grooves of the diffraction grating relative to the ordered rows of mini-emitters should affect the level of heat detected from the upper part of the resonator directly attached to the thermocouple. In this part of her difficult experiment, M A Levitskaya relied on the extensive experience gained in her first work studying the attenuated secondary radiation of a rectilinear resonator in the centimeter wavelength region [66–68].

Experiments performed with a setup with a diffraction grating having conducting 'grooves' showed that, when the grooves of the grating were located parallel to the rows of the emitter, the deflection of the galvanometer was weak, and when they were perpendicular to them, it was significant. This original experimental technique proved the wave nature of the radiation generated by the mass emitter. Thus, the result of experiment [1] was proof of the possibility of generating submillimeter waves with a wavelength of 0.1–1.0 mm using an ordered system of electrically excited mini-emitters. The main drawback of [1] is the lack of a spectroscopic (spectral) analysis of the generated radiation.

4. A A Glagoleva-Arkadieva's mass emitter

Before discussing M A Levitskaya's later work, let us consider the results of the original experiments performed by A A Glagoleva-Arkadieva [23, 24]. Study [23] was published on May 3, 1924, and [24] was received by the editorial board of *Nature* on March 17, 1924. It is believed that the ideologist of the approach developed in these papers was V K Arkadiev [21]. The method for generating submillimeter waves was developed by A A Glagoleva-Arkadieva after 1914, and was also based on the principle of a mass emitter, but of a different, no less original, design. Use was made of brass or aluminum filings ranging in size from 0.5 to 0.14 mm with a significant admixture of small ones, up to 0.04 mm, placed in a liquid dielectric (machine oil). In this case, as seen in Fig. 6, the emitters, excited in a spark, had to be constantly replaced; to do this, a small part of a carbolite wheel A rotating with the help of a motor was immersed in a 'mushy,' viscous mass, constantly stirred by a stirrer. The wheel captured the vibrating mass, so that a 'bus' appeared on it, the upper part V of which was continuously replaced when the wheel rotated.

Two wires ff supplied this bus with high voltage from the inductor, and the discharges passed through the vibrating mass V. Due to the discharges, electrical oscillations arose in the filings, the period of which depended on the size of the

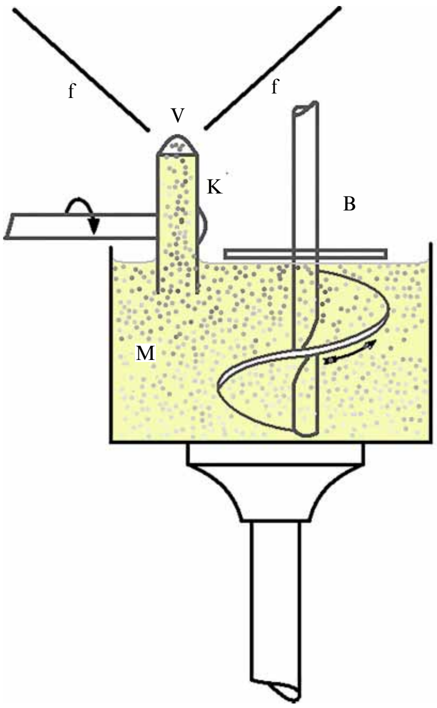

Figure 6. A A Glagoleva-Arkadieva's mass emitter [23].

metal particles. The spectrum of radiation generated by this mass emitter was obtained by the interferometric method, and the possibility of producing submillimeter waves was demonstrated. Their spectrum was obtained down to 82 μm, i.e., up to frequencies of about 3.7 THz [23, 24].

M A Levitskaya's and A A Glagoleva-Arkadieva's achievements in solving the problem of submillimeter wave generation were especially noted immediately after the publication of the results in their work, which could be regarded as a forerunner of the discovery of submillimeter waves in 1923 by E Nichols and J Tear [72]. Study [72] was published in 1925, after the sudden death of E Nichols while giving a report devoted to a discussion of his results of submillimeter wave generation in 1924 [72]. It was especially noted that evidence "... of electric wave radiation of less than 1 mm has also been obtained recently by M Levitskaya (*reference to work* [1]), who has studied the total radiation emitted by small spheres in a spark discharge, and by Arkadieva (*reference to work* [24]), who has generated electric waves by passing a discharge through a paste of metal filings." It should be noted that the overtone method, the principles of which were experimentally developed by M A Levitskaya [1], was implemented in [72]. Submillimeter electromagnetic waves were generated by a similar source [46, 47], which was a pair of miniature tungsten cylinders with micrometric control of the spark length and a cooling system. By 'tuning' the emitter and resonator to the same wavelength, corresponding to one of the higher harmonics with respect to the fundamental oscillations of the emitter, an overtone spectrum with wavelengths of up to 0.22 mm was obtained using the interferometric method [72].

After returning from Tashkent to the Leningrad Physicotechnical X-ray Institute, M A Levitskaya obtained the radiation spectrum from her mass emitter using a diffraction grating; the results of the experiment were published in 1926 [2, 3]. The spectrum of the mass emitter used in [1] contained a system of maxima from 0.47 mm to 0.034 mm. Similar measurements for a mass emitter, which included pieces of molybdenum wire, the length of which varied within 0.1–0.4 mm, made it possible to obtain a system of maxima over the entire submillimeter section with a significant overlap in the IR region (from 1.0 mm to 0.03 mm) [2, 3]. The results of studies [2, 3] confirmed all the results and assumptions made in [1].

Later, throughout her active scientific work, M A Levitskaya performed interesting studies on the nature of submillimeter radiation and the mechanisms of its occurrence in a mass emitter, including in A A Glagoleva-Arkadieva's mass emitter (Table) [4–8]. Estimates were made of the power of submillimeter waves generated by the mass emitter in both cases, and its value of 10^{-5} W was obtained.

The unified nature of waves excited by the Hertz method and those from thermal sources was finally proved in [4]. The method of residual rays was used to establish the shortest-wavelength radiation from a mass emitter in the region of 30–90 μm, and it was proven that, regardless of the method of generating the radiation, submillimeter waves have the same nature — they are electromagnetic waves.

Immediately after her first experiments, M A Levitskaya studied for several decades the mechanism of the emergence of submillimeter waves from a mass emitter and sought an effective source of waves in this range [7, 8, 73, 74]. She demonstrated that, along with weak overtones of 'Hertzian' oscillations of small metal particles in a mass emitter, there is significant radiation of hot dielectric vapors (in the resulting arcs) and electron oscillations in a spark [7, 8]. Particular attention in this work was paid to the possibility of generating submillimeter radiation by creating conditions for the oscillatory motion of free electrons in a spark gap in a vacuum and in porous substances.

Other parts of M A Levitskaya's work were devoted to the search for effective registration of submillimeter waves, to the properties of the Te/Bi thermocouple, to the thermoelectric properties of the selenium–copper alloy from the point of view of application for registration of submillimeter waves, and even to the effect of submillimeter waves on a photographic plate [75–77]. In the last case, it turned out that submillimeter waves are capable of destroying the centers of a latent image, due to which white spots appear on exposed photographic films, the shape of which corresponded to the geometric properties of the source. For example, this method was used to detect glow with wavelengths of 75 and 136 μm [77].

Table. Comparison of submillimeter waves generated using mass emitters [8].

	According to A A Glagoleva-Arkadieva								According to M A Levitskaya							
λ, μm	900	450	300	255	180	150	128.8	81.8	470	400	330	270	185	136	75	34
Intensity J, rel. units	3	5	84	3	25	100	13	1.6	40	90	60	80	90	100	30	5

Maria Afanas'evna Levitskaya
(April 1, 1883–March 7, 1963).

Aleksandra Andreevna Glagoleva-Arkadieva
(February 16, 1884–October 30, 1945).

5. Conclusions

A comparison shows that the experiments of Maria Afanas'evna Levitskaya and Aleksandra Andreevna Glagoleva-Arkadieva are completely independent and each is original. The first results were published almost simultaneously. Therefore, they both can be considered to be the authors of the discovery of the central part of the terahertz range (0.3–0.8 THz). Thus, they confirmed the assumption made earlier by other physicists about the identity of thermal radiation and radio emission in the submillimeter wave range. It is worth noting the highest level and absolute originality of the experiments of some of the first female Russian physicists, as well as their dedication and courage.

This paper is published in the year of the 100th anniversary of the discovery of submillimeter electromagnetic waves, which proved the continuity of the electromagnetic wave scale. The paper is dedicated to the blessed memory and 140th anniversary of the birth of some of the first female physicists in Russian and world science, Maria Afanas'evna Levitskaya and Aleksandra Andreevna Glagoleva-Arkadieva, who managed to be at the forefront of world science in difficult times for the country.

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