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*Research Article*

# Application of a Surface Waveguide in Microwave Drying Units of the Agribusiness Industry

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In the last two decades, the electromagnetic field of the microwave range has been successfully introduced into various branches of the agribusiness industry as one of the most promising and advanced technologies for drying manufactured products. In this regard, the article proposes a new microwave irradiation technique for drying various objects based on a surface waveguide's properties. The paper analyses the main links that make up the surface waveguide as a microwave irradiation system and shows the ways of their implementation. The article describes the advantages of applying a vibratory device for exciting a surface wave, using a re-emitting antenna array, and operating a single conductor with a dielectric coating as a surface waveguide. Such advantages make it possible to introduce microwave drying units with the required distribution of electromagnetic field energy along the irradiated material, small dimensions, high drying quality, and low price.

## 1. Introduction

Currently, the possible options for microwave energy applications are increasingly expanding. Microwaves are used in many branches of the food industry [1, 2], pharmacology [3], as well as agriculture [4]. The microwave drying of grain [5–7], fruit, potatoes [8], and other manufactured food products [9]. Microwave drying units are widely used in auxiliary industries for drying wood [10], paint coatings, and others [11–13].

The cited work [14] discusses the pseudoliquefaction technology in microwave drying vegetables and fruits. This technology enhances the uniformity of the microwave radiation impact on drying objects. Currently, a range of drying units based on the VFD technology has been developed. Such drying units have their advantages and disadvantages.

The use of hot air in microwave drying of products with a low moisture content significantly improves the uniformity of drying irradiated products. Dehydrating vegetables and fruits is significantly accelerated in microwave vacuum drying with pulsed compressed air spraying. The uniformity of microwave drying of vegetables and fruits is also improved by evenly distributing the material during vibrational pseudoliquefaction.

The work [15] proposes a microwave drying unit based on pseudoliquefaction technology. To ensure uniform irradiation of the dried material, the unit contains six horn radiators in conjunction with magnetron generators. A vibrational motor with adjustable vibration frequency is installed in the setup, bringing the materials to a more homogeneous pseudoliquefied state.

The work [16] describes the technical aspects of microwave sublimation drying of various food products. It proposes designs for experimental continuous-action setups with microwave sublimation drying in a vacuum. Vacuum sublimation drying of food products is one of the best methods for dehydrating material that yields high-quality final products.

Despite its apparent advantages, sublimation drying using microwave heating has several drawbacks. Designing and manufacturing microwave sublimation dryers are a complex task due to the high probability of design errors, which can lead to the occurrence of plasma arcs. In the event of an arc discharge, microwave power is wasted, and the product is charred, significantly damaging the final product. To prevent plasma arcs, it is necessary to ensure uniform irradiation of the entire surface area of the drying materials with microwave energy.

A microwave setup [17] is known for the staged drying of bulk agricultural materials. Here, a three-stage drying mode of the raw material is implemented through the unique design of tiered toroidal resonators, which are made as four-sided prisms within a prism through which a ceramic pipe with a dielectric screw conveyor passes to move the raw material by gravity when warm air is blown through. This variant partially addresses the issue of uniform field distribution in the bulk material layer. However, this problem still needs to be solved.

The analysis of existing drying techniques and designs of drying units used in many branches of the food industry showed that these techniques and designs have several significant disadvantages, including material overheating leading to overdrying, large dimensions, inconvenience of chamber transporting, and low efficiency.

In addition, the drying units used today are designed for a sufficiently large throughput volume. In conditions of small farms, where emergency, low-cost drying of small amounts of grain, wood, vegetables, fruit, potatoes, etc. is required, the use of dryers of this type is impractical.

The purpose of the research is to create new methods of microwave energy irradiation of products in the food industry to increase their drying efficiency by means of a surface waveguide.

## 2. Materials and Methods

Standard microwave drying units usually contain horn-shaped emitters, which are placed in such a way as to ensure uniform drying of certain objects. At the same time, the uniformity of the above drying method leaves much to be desired, since the horn emitters themselves have an uneven distribution of the field in the opening, and thus they should be installed at some distance from each other. According to experience, extended objects require uniform drying. This may include wood drying, conveyor grain drying, soil treatment, etc. According to the authors, the most suitable tool for solving this problem is a surface waveguide [18]. The feature of a surface waveguide is that upon excitation, surface waves of the $E_{00}$-type electromagnetic field can MY installed near the wire. The majority of the electromagnetic field energy for the surface wave is localized within the cylindrical region surrounding the waveguide wire, with a radius no greater than the wavelength $\lambda$. There is a one magnetic component $H_\phi$ and two electrical components $E_r$, $E_z$ in the configuration of the surface waveguide field. The configuration of the waveguide field is shown in Figure 1.

Placing a dielectric object in the surface waveguide field leads to a certain part of the energy being absorbed by the object and, accordingly, to heating and drying.

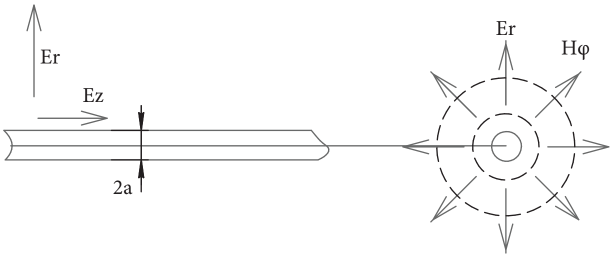


Figure 1: Configuration of the surface waveguide field.

A wire dielectric coated is an open surface waveguide only if special generation systems are installed on it to create and maintain a surface wave. Hence, the creation of such wave $E_{00}$ generation systems is very significant. It is the excitation system that determines the configuration and parameters of the wave $E_{00}$, as well as the range properties of the surface waveguide.

This study uses the method of Kismereshkin and Lobova, and the methods description partly reproduces their wording [19–21].

A horn exciter is a fairly perfect model interpreting the smooth transformation of the coaxial line wave into the wave $E_{00}$ of the surface waveguide. However, there are several significant drawbacks to this excitation device. The length of such an excitation device is 2 $\lambda$, the output diameter is about two effective radii. In addition, the structure is metal-intensive, and the manufacture of the horn requires some special equipment. To eliminate the presented disadvantages, the authors have developed a vibratory device for exciting a surface waveguide from a set of half-wave vibrators connected by their tops into the form of a “fork.” The proposed wave $E_{00}$ generation system is shown in Figure 2.

It is worth noting that the proposed generation system can work both for transmission and reception. The vibratory generation system shown in (Figure 2) can be used in conjunction with a flat reflector made in the form of a disk. This system is installed perpendicular and symmetrically relative to the surface waveguide wire (Figure 3).

To ensure proper coordination with the feeder, the group of vibrators must be positioned close to the reflector, at a distance of 0.15 times the wavelength. This is because the total electrical length of the emitter is equivalent to the wavelength, and the feeder has a wave resistance of 50 ohms.

Figure 4 shows the design of the experimental unit that was constructed to evaluate the performance of the surface wave generation system.

To conduct the experiment, the surface wave generation system (3) was supplied with a 915 MHz signal from the generator (1) through the feeder circuit (2). The flat reflectors (4) are located perpendicular and symmetrically relative to the waveguide wire (5). The energy generation system itself does not emit radiation. However, a potential area near the wire formed by the near ends of the vibrators leads to the formation of current on it. As a result, a surface wave is formed around the wire, which tends towards the other end of the wire.

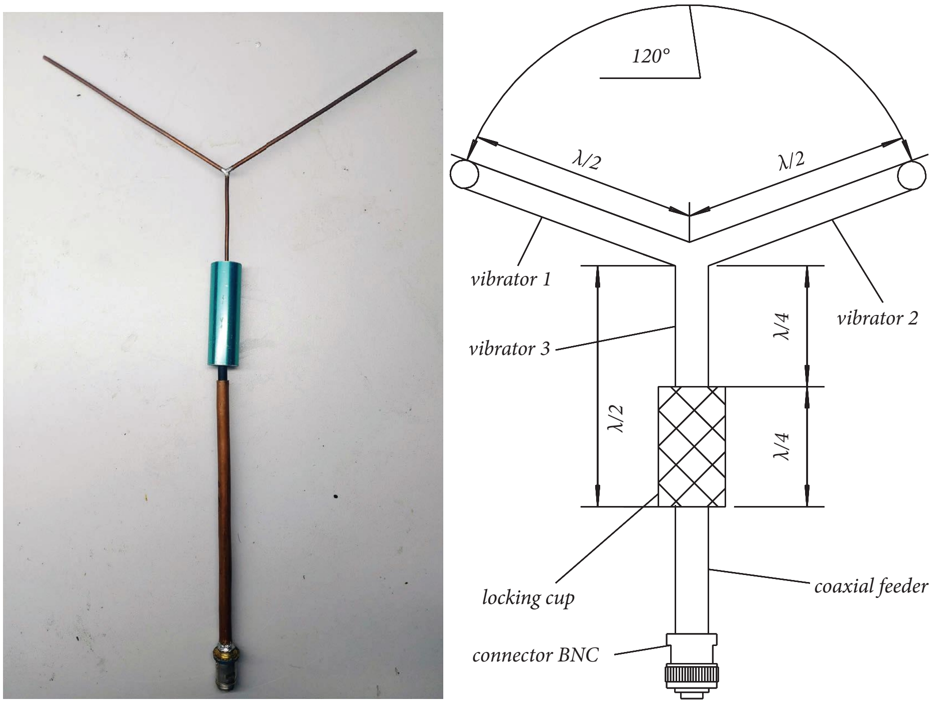


Figure 2: Wave $E_{00}$ generation system.

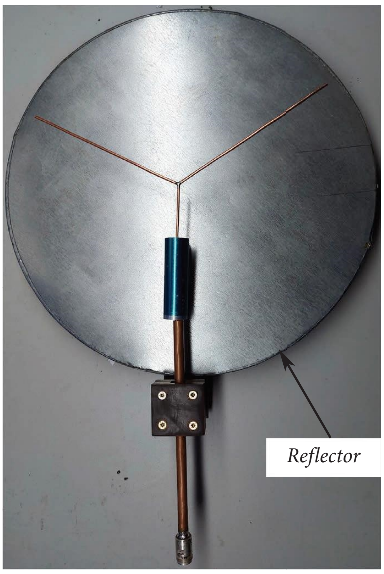


Figure 3: Surface wave generation system in combination with a flat reflector.

Figure 5 shows the propagation pattern of the electromagnetic field of the $E_{00}$ wave along the waveguide wire.

The opposite end of the waveguide, a comparable surface wave generation system (6) is installed, specifically designed for receiving purposes. The device (7) records the received signals.

The level of the received signal compared to the signal that passed through the waveguide path of the same length was 3 dB lower, which indicated the effectiveness of the proposed surface wave excitation device.

It should be noted that the manufacture, installation, and operation of a surface waveguide with the proposed surface wave excitation device is simpler and economically more profitable compared to those previously used.

Another feature of the surface waveguide is that the inhomogeneity placed in its field leads to partial re-emission and absorption of the waveguide energy. At the same time, it is possible to implement the modes of both maximum re-emission and maximum absorption of microwave energy. In this regard, with the help of several inhomogeneities, it is possible to form a certain distribution of the re-emitted field with a concentration of radiation in a certain direction.

In our case, to ensure uniform, high-quality drying of extended objects, it is necessary to ensure uniform distribution of microwave energy along the length of the irradiated object located. And since the introduction of any inhomogeneity into the surface wave field causes the re-emission of energy into the environment, the system of inhomogeneities located along the surface waveguide wire shall be a simple antenna array. Consequently, the uniformity of the effect of microwave radiation on an extended drying object can be achieved by installing a re-emitting antenna array coaxially with a waveguide wire consisting of several re-emitting vibrators. The flowchart of the re-emitting antenna array consisting of $N$-vibrators is shown in Figure 6.

The re-emitting antenna array shown in Figure 5 works as follows. When the waveguide is excited, the electromagnetic field corresponding to the surface wave appears, containing both longitudinal and radial components of field. Vibrators are positioned along the tension lines of the $E_z$ component on the wire. These vibrators induce the corresponding electric current and emit the energy of the

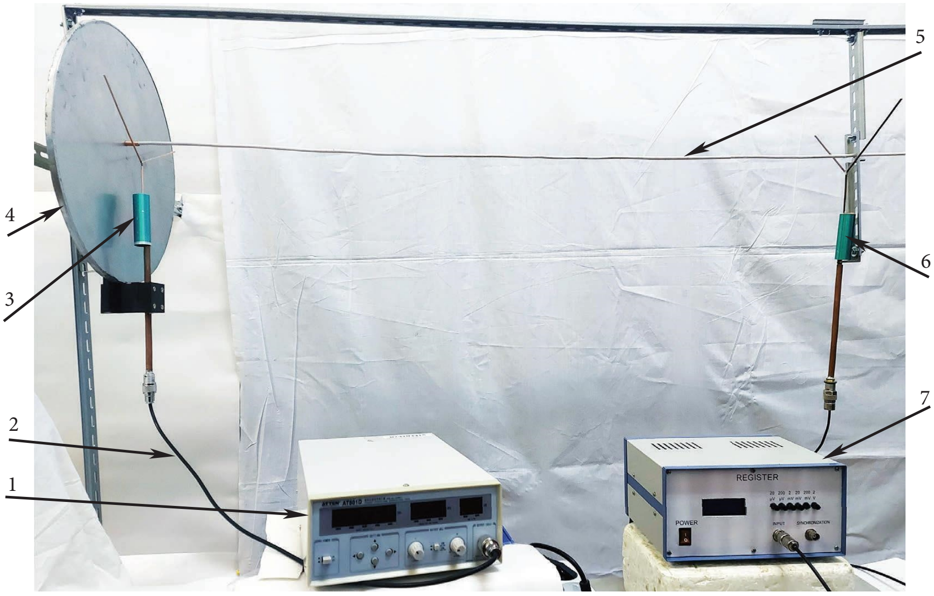


Figure 4: Surface wave generation system in combination with a flat reflector. (1) generator; (2) feeder; (3) generation system; (4) reflector; (5) waveguide wire; (6) second generation system; (7) recorder.

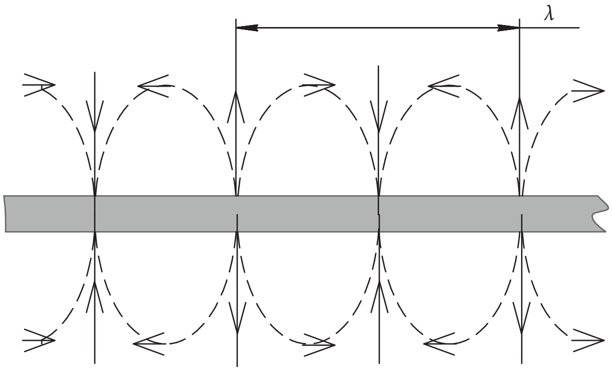


Figure 5: A picture of the propagation of the electromagnetic field of the $E_{00}$ wave along the waveguide wire. $r$ is the radius of propagation of the electromagnetic field of the wave; $a$ is the radius of the waveguide wire.

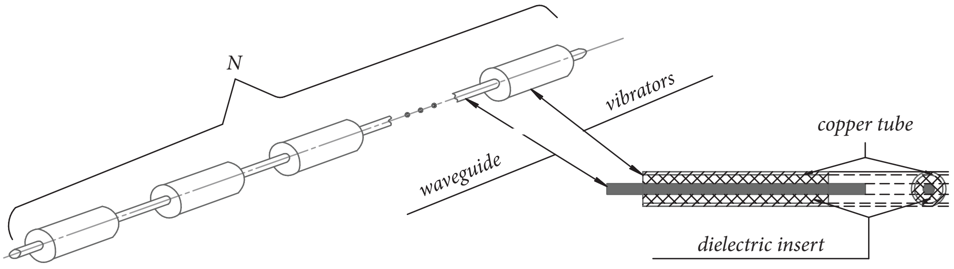


Figure 6: Re-emitting antenna array flowchart.

waveguide field once again. Vibrators located on the wire to establish communication with the waveguide are having a cylindrical shape. A current is induced in them of the action of the component $E_z$. The component $E_r$ not induce an current in the vibrators under consideration since the angle between the axes of the vibrator and the component $E_r$ of is 90.

The cylindrical vibrator (Figure 6) is a metal tube with a dielectric insert directly attached to the waveguide wire. Such a vibrator will re-emit energy in all directions.

When constructing a re-emitting antenna array based on a surface waveguide, the following should be taken into account: the energy of the wave transmitted by the waveguide from the generation system to the dissipative loading is converted into energy emitted by each vibrator of the antenna array. Therefore, if the power $P_0$ is supplied to the first vibrator, then the power equal to is supplied to the second one:

$$P_2 = P_0 - \mathrm{P}_1, \tag{1}$$

where $P_0$ is the power supplied to the waveguide, $P_1$ is the power taken from the surface wave by the first vibrator, and $P_2$ is the power supplied to the second vibrator.

Similarly, the process can be carried out for all subsequent $N$-vibrators. Each subsequent vibrator will be supplied with less power than the previous one. However, to uniformly distribute field energy along the aperture of the antenna array, when all elements of the antenna array must emit the same power, it is necessary to provide different coupling coefficients with the waveguide wire for each vibrator. The coupling coefficient of a cylindrical vibrator with a waveguide wire depends on the radius of the wire on which it is placed, and on the vibrator's length. It was established that the smaller the radius and the longer the vibrator, the greater the coupling coefficient $k$. Changing the length of the cylindrical vibrator is the most convenient way to achieve the required values of the coupling coefficient.

The distribution of energy across all vibrators of the antenna array can be described by the expression:

$$\begin{aligned} P_0 &= P_0 k_1 + (P_0 - P_0 k_1) k_2 \\ &\quad + (P_0 - P_0 k_1 - (P_0 - P_0 k_1) k_2) k_3 + \ldots + \delta, \end{aligned} \tag{2}$$

where $k$ is coupling coefficients, and $\delta$ is the remaining power in the waveguide.

It follows from equation (2) that the first cylindrical vibrator of the antenna array should take the minimum power, and the last Nth vibrator should take the maximum possible share of power from the waveguide (about half of the power supplied to it), and the residual power in the waveguide enters the dissipative loading.

The phase distribution depends only on the distance at which the vibrators are located relative to each other. For all vibrators to have the same phase, the distance between their centers should be equal to the wavelength $\lambda$.

In this case, the surface waveguide can be in two states: in the traveling wave mode and the open resonator mode. In the first case, the traveling wave mode is achieved by loading the waveguide to a consistent load. Another variant of excitation of the surface waveguide is carried out through an open resonator formed on its site.

Since it is of particular interest to operate in the mode of re-emission of a surface wave using an antenna array for operating a surface waveguide. For this purpose, the unit with a segment of the surface waveguide shown in Figure 4 was modified by installing an umbrella in the form of a dipole antenna, from which signals were taken and transmitted to the receiver. Cylindrical vibrators were also installed on the waveguide wire. This made it possible to measure (study) the directly re-emitted field by separating it from the surface wave field. In this case, the standing wave mode is formed with the help of a second reflector installed at the end of the waveguide. It is worth noting that the reflector can move freely along the line due to an electrical short circuit with the waveguide wire through a quarter-wave segment made in the form of a tube that is placed on the waveguide wire. In this way, both ends of the waveguide are connected to reflectors.

The unit for studying the properties of the surface waveguide is shown in Figure 7.

Under the described states of the surface waveguide, the following experimental studies were performed:

(i) Excitation of the line with a single re-emitting vibrator in modes with a dissipative loading and an open resonator
(ii) Excitation of the line with two re-emitting vibrators in modes with a dissipative loading and an open resonator

The initial data of the surface waveguide are as follows:

(i) A copper tube is used as a wire
(ii) Wavelength in the waveguide $\lambda = 0.32$ m
(iii) Device length $L/\lambda \approx 7$
(iv) Field frequency $f = 915$ MHz
(v) Experimental design parameters of the waveguide $\mathrm{t}/\lambda = 0.62 \cdot 10^{-3}$; $t = 2 \cdot 10^{-4}$ m ($t$ is the thickness of the dielectric coating); $d = 4.4 \cdot 10^{-3}$ m ($d$ isthe diameter of the waveguide wire); $d/\lambda = 1.37 \cdot 10^{-2}$ m

The results of the research are shown in Figure 8. In Figure 8(a), one re-emitting vibrator was installed on the waveguide wire, and experiments were carried out to study the re-reflected field from a cylindrical vibrator in two modes with a load and in the open resonator mode. A similar experiment is shown in Figure 8(b) with only two cylindrical vibrators used in the line.

As a result of performing experiments with a surface waveguide at a frequency of 915 MHz, the subsequent outcomes were attained:

(i) In the open resonator mode, the field distribution exhibited a variation of ±12 dB when using a single re-emitting vibrator, while in the load mode, the unevenness of the field distribution was ±7 dB
(ii) In the open resonator mode, the field distribution exhibited a variation of ±13 dB when using two re-emitting vibrators, while in the load mode, the unevenness of the field distribution was ±3 dB

The subsequent endeavors concentrated on the creation of an array of re-emitting antennas, which comprised multiple cylindrical vibrators and a waveguide wire.

The experiment was carried out as follows: a cylindrical vibrator was installed on the wire of the surface waveguide at a distance of one wavelength from it, the receiving antenna (horn antenna) was fixed, and when the length of the vibrator changed, the power received by the horn was recorded. The length of the vibrator changed until it took

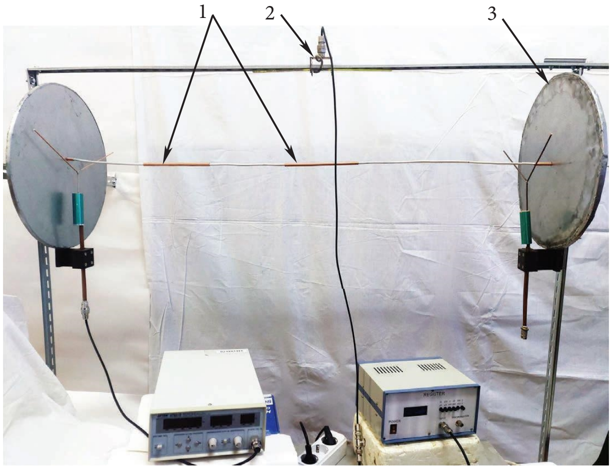
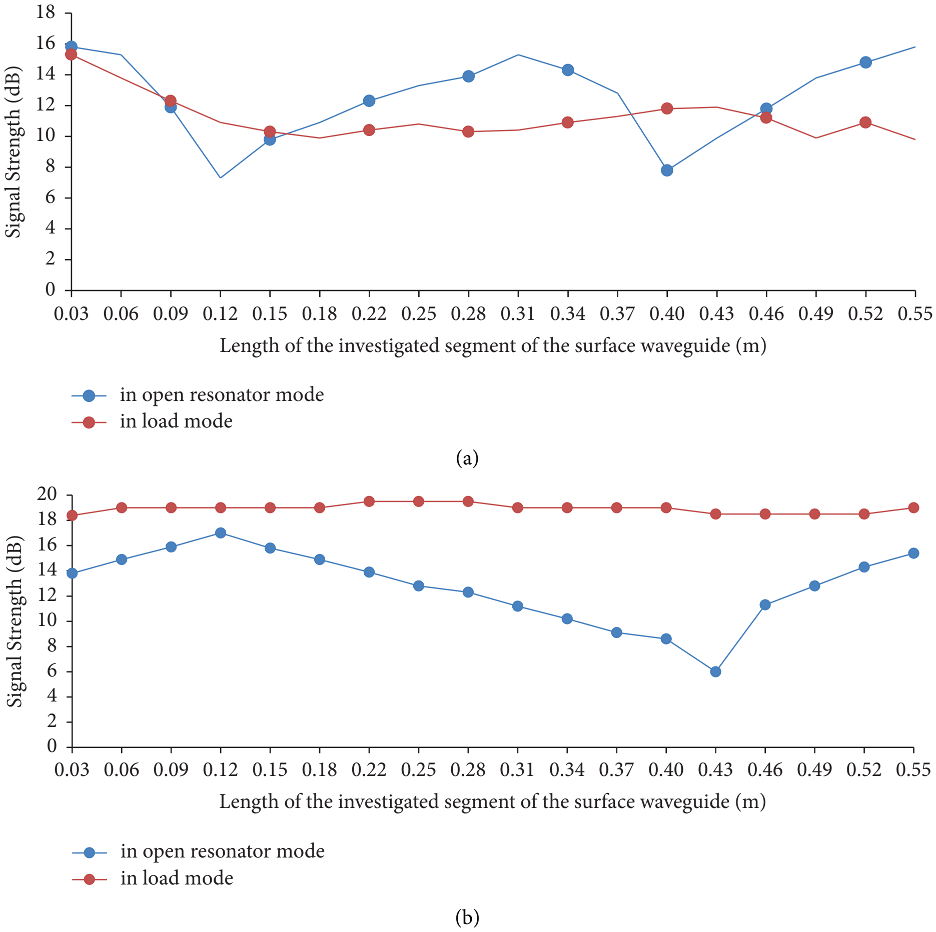


Figure 7: Design of an experimental setup for studying the properties of a surface waveguide. (1) cylindrical vibrators; (2) umbrella in the form of a dipole antenna; (3) is second reflector.



(a)

(b)

Figure 8: Dependences of the electromagnetic field distribution in the surface waveguide (a) one vibrator is installed and (b) two vibrators are installed.

10% of the power supplied to the waveguide from the line. The value of 10% was chosen for the convenience of calculations. Next, a second vibrator was installed and its length was determined, at which it took 10% of the power transmitted by the open waveguide. A similar operation was performed sequentially for all elements. It should be noted that the amount of residual power supplied to the ballast load was about 10% of the total power supplied to the waveguide. A fragment of the developed re-emitting antenna array is shown in Figure 9.

Figure 9: Fragment of a re-emitting antenna array.

Another essential task in developing microwave drying systems is to concentrate the energy of the electromagnetic field in the required irradiation zone and protect the maintenance personnel from harmful microwave radiation. The geometric structure of the surface waveguide allows the problem to be solved with the help of a reflector made in the form of an elliptical cylinder with two focal lines, F1 and F2.

Figure 10 shows the diagram of the microwave radiation concentration system on the irradiated object using a reflector in the form of an elliptical cylinder.

In this case, it is proposed to use a closed conducting shell as an elliptical cylinder and place a re-radiating antenna array on one focal axis and the irradiated object on the other. This allows for more voluminous microwave irradiation and reduces the energy dissipation, vital for protecting maintenance personnel.

The dimensions of the elliptical cylinder are chosen as follows: the length of the cylinder is based on the length of the irradiated objects, and the transverse dimensions are calculated so that the minimum distance from the axis of the antenna array to the cylinder shell is greater than the wavelength. This dimension depends on the operating frequency of the drying unit.

The cylinder can be made of single-line conductors. The smaller the distance between the conductors, the greater the attenuation level of the emitted field required by the unit. Usually, this distance does not exceed $0.1\lambda$. The most suitable solution is when a single-line grid of stretched wires along the generatrices forms the elliptical cylinder. Here, the entire system is placed in a metal casing, the construction of which is chosen based on manufacturing and operational convenience. The elliptical cylinder is terminated on the sides by flat-parallel conducting walls. Inside, these walls have high conductivity and serve as reflectors for excitation and energy absorption devices into the ballast load; outside, exciters and ballast loads are placed, respectively.

## 3. Results and Discussion

An inexpensive small-sized surface wave generation system was developed as a result of the conducted research.

Based on the practical research, a conductor and its dielectric coating were selected for the manufacture of a surface waveguide. A fragment of a copper tube with a steel core was examined. At the same time, the tube outside was covered with a PTFE-4 layer. The results of theoretical calculations and experimental work show optimal values of the boundary radius of the surface wave propagation near the waveguide with a conductor diameter of 4 mm and a dielectric coating thickness of 0.2 mm. The findings of the investigations are presented in Table 1.

Besides, based on practical experiments, a nine-element-elementre-emitting antenna array was developed from cylindrical vibrators coaxial with a wire at a frequency of 915 MHz. The lengths of vibrators at which the re-emitted powers are equal are indicated in Table 2. The application of such an antenna array in drying units will allow for better and uniform drying of long materials and solve the problem of local overdrying of wood grain material, leading to different flaws.

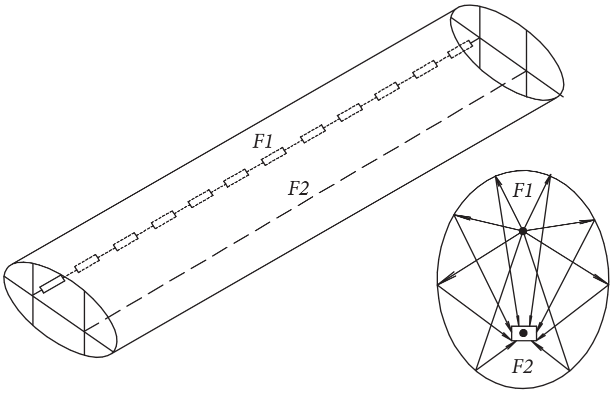


Figure 10: System for concentrating energy from an elliptical cylinder and a surface waveguide.

Table 1: Parameters of the surface wave in the waveguide at the allowed frequency range for heating devices.

| Frequency (MHz) Parameters | 433 | 915 | 2450 |
|---|---|---|---|
| $r_0/\lambda$ | 1.33 | 0.268 | 0.216 |
| $r_0$ (m) | 0.920 | 0.086 | 0.026 |

$r_0$ is the radius of the surface wave energy propagation near the waveguide wire.

As a result of the research, a radiation pattern of a nine-element re-radiating antenna array was obtained, as shown in Figure 11.

Based on the experiment, the field distribution of the surface wave over the re-radiating vibrators of the nine-element antenna array was evaluated.

A horn antenna, which receives the field of the investigated nine-element antenna array, was moved along the array at a distance of $\lambda$. The receiver recorded the signal received by the horn antenna. A graph was plotted based on the measurement results of the field amplitude along the vibrators of the antenna array (Figure 12).

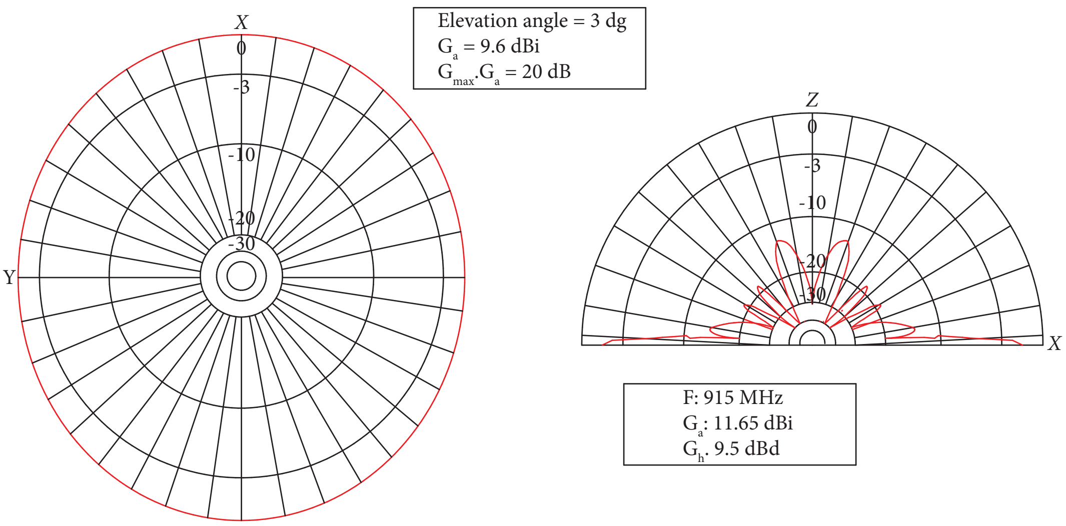
The results of the experimental verification of the developed nine-element vibrator antenna array are presented in Table 3.

According to the source [22], the horn radiator has the characteristics presented in Table 4.

Particular attention should be paid to the dimensions and weight of the horn radiator. The weight of the radiator is

Table 2: Length of cylindrical vibrators.

| Vibrator number | Vibrator length ($\lambda$) |
|---|---|
| 1 | 0.27 |
| 2 | 0.272 |
| 3 | 0.276 |
| 4 | 0.279 |
| 5 | 0.28 |
| 6 | 0.284 |
| 7 | 0.289 |
| 8 | 0.292 |
| 9 | 0.295 |



E - plane H - plane

Figure 11: Radiation pattern of a nine-element re-radiating antenna array.

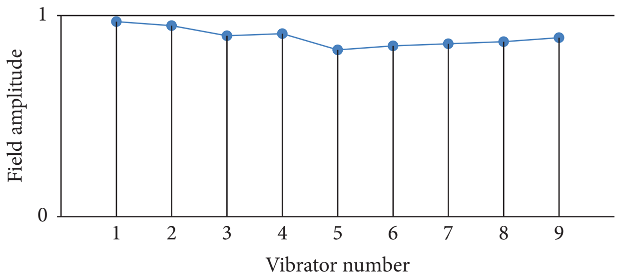


Figure 12: Energy distribution by the re-emitting vibrator of the antenna array.

Table 3: Characteristics of the nine-element antenna array based on the surface waveguide.

| Parameters | Value |
|---|---|
| Operating frequency (MHz) | 915 |
| Realized gain (dBi) | 11.6 |
| Impedance (ohms) | 50 |
| SWR | 1.4 |
| Material | Copper, PTFE-4 |
| Weight (kg) | 3.2 |
| Dimensions ($H \times W \times L$) (m) | $0.327 \times 0.327 \times 2.69$ |

Table 4: Characteristics of the EMC horn emitter.

| Parameters | Value |
|---|---|
| Operating frequency (MHz) | 915 |
| Realized gain (dBi) | 12 |
| Impedance (ohms) | 50 |
| SWR | 1.6 |
| Material | Aluminum |
| Weight (kg) | 16.5 |
| Dimensions ($H \times W \times L$) (m) | $0.934 \times 0.69.4 \times 0.978$ |

more than five times greater than the weight of the proposed system based on the surface waveguide. Manufacturing such radiators requires highly technological equipment and special production conditions. The proposed surface wave generation system is simple to manufacture and does not require specialized equipment. Using surface waveguide-based systems in drying units will significantly reduce the weight of the units and simplify their construction.

The cost of microwave drying units is also an important issue. Let us consider a simple example: according to sources [22, 23], the cost of a horn radiator, designed for a frequency of 915 MHz and used in traditional microwave

Table 5: Main properties of a microwave grain dryer developed based on the properties of a surface waveguide.

| Parameters | Value |
|---|---|
| Dimensions of the dryer ($H \times W \times L$) (m) | $0.8 \times 1 \times 2.3$ |
| Dryer weight (kg) | 120 |
| Drying temperature (°C) | 5–150 |
| Productivity depending on the mode of microwave processing within (t/h) | 0.3–1.5 |
| Power consumption, max (kW) | 30 |
| Materials to be dried | Wheat, millet, barley, rye |
| Humidity of the final product at the outlet (%) | 14-15 |

drying units, ranges from $875 and higher. To ensure uniform drying of products in units described in the works [5, 15], it is necessary to use from 1 to 6 horn radiators, depending on the purpose and dimensions of the unit. Thus, the unit cost inevitably increases. In turn, the vibrator excitation system proposed by the authors for the $E_{00}$ wave electromagnetic field is very simple to manufacture and does not require specialized equipment and production conditions. Based on preliminary calculations, the proposed excitation system costs at most $50. Therefore, the overall cost of drying units manufactured using surface waveguide technology can be reduced from $825 to $5000.

Based on the results of the study of the properties of the surface waveguide, a group of scientists from North Kazakhstan University conducted a preliminary calculation of the parameters of a microwave grain dryer, which is based on: a vibratory excitation device of the "fork" type, a surface waveguide, which is a wire with a dielectric coating, a re-emitting antenna array consisting of several cylindrical vibrators. The results of the preliminary calculations are in Table 5.

## 4. Conclusions

The conducted experiments confirm that the proposed methods of microwave radiation excitation and uniform radiation distribution over the entire irradiated material make it possible to design more efficient microwave dryers for the agribusiness industry or significantly improve existing ones. The results also contribute to developing other industrial areas, particularly the dielectric heating of bitumen, ceramics, and medicinal herbs.

In comparison with existing systems operating on microwave energy, the main advantages of microwave dryers with surface waveguides include the following:

(i) Uniform drying of extended objects (large-sized lumber or conveyor drying of grain) that does not lead to their local overheating or fire

(ii) Minimal dimensions and metal consumption compared to traditional drying plants

(iii) Simplicity of design and reliability of the microwave excitation system

(iv) Minimum radiation power and unused power entering the dissipative loading

(v) Light weight and high transport capacity of the chambers

## Data Availability

All data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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