

Installation for Concentrated Uniform Heating of Objects by Microwave Radiation

Jacek Cieslik, Vladimir Kismereshkin, Ekaterina Ritter, Alexey Savostin, Dmitry Ritter and Nabi Nabiyev

Abstract—A design of microwave installation for energy concentration on a surface of a heated object is proposed. In the installation a dipole lattice on the basis of a single-wire transmission line is used which is located inside of reflector in a form of specular parabolic conducting cylinder. The heated object is placed in the area of microwave energy concentration.

In the article a waveguide field of a surface wave in a reradiation mode is explored. The surface wave is reradiated by a group of vibrators coaxial with the waveguide wire. Results of experimental studies of field distribution along the waveguide operating in various modes are presented. The possibility of efficiency increase in reradiated field and its adjustment by contactless movement of reflector is shown.

Keywords—single-wire transmission line, microwave radiation, excitement of a surface wave, wave guide, vibrator, reflector

I. INTRODUCTION

IN many industries, the production uses microwave radiation. Among the objectives of applying microwave radiation, it is extremely important to provide an object with a concentration of microwave radiation on its surface. The solution of such task is extremely relevant for the woodworking industry, agriculture and other industries.

In the woodworking industry a problem solution of high-quality, fast and low-cost wood drying remains relevant despite the achieved results. Recently, interest in the microwave hardwood drying has increased. In the content of work [1] for wood drying in the installation it is proposed to use a combined principle of operation including convective and dielectric heating.

In work [2] it is proposed the microwave vacuum drying that allows to dry up the cylindrical logs with initial humidity of 80% to final moisture content of 15% with a decrease in energy consumption. Ultra-high radiation, acting on wet wood, leads to boiling of moisture which creates an excessive pressure. This pressure leads to extrusion of small droplets of moisture from capillaries and to formation of steam. The formed moisture is carried out of the wood by a diffusive flow. The hot steam coming out of wood creates a heat curtain that prevents the temperature of the wood from falling.

Jacek Cieslik, professor at AGH University of Science and Technology, Krakow, Poland. e-mail: cieslik@agh.edu.pl

Vladimir Kismereshkin (e-mail: vkismereshkin@gmail.com), Ekaterina Ritter (e-mail: kriter315@gmail.com), Alexey Savostin (e-mail: alexey.savostin@gmail.com), Dmitry Ritter (e-mail: dritter@gmail.com) and Nabi Nabiyev (e-mail: nabi nabiyev@mail.ru) are with M. Kozybayev North Kazakhstan state university, Petropavlovsk, the Republic of Kazakhstan.

In a small-sized dryer [3] which allows achieving a high-quality dried material at a significant drying rate, a working chamber containing a magnetron unit and an electromagnetic energy distribution system in the microwave range along the length of the chamber are used.

The used devices for microwave wood drying are characterized by difficulties in concentrating the power of generators and a distribution of energy density along the chamber in which the object is irradiated.

II. AN OVERVIEW OF THE INSTALLATION FOR MICROWAVE DRYING

An installation based on the use of a single-wire microwave transmission line is proposed for microwave drying. In such installation the heated object is placed in the field of the surface wave E_{00} .

Application for microwave drying of the waveguide in the form of a single-wire transmission line in comparison with traditional methods has the following advantages:

- in achieving the minimum values of the metal intensity of the installation, the emitted power and the power that is required to be disposed of;
- ensuring uniform heating of long drying objects;
- a significant reduction in the cost of installation for wood drying.

The use of waveguide in the form of a single-wire transmission line allows the development of new microwave drying devices. In our case it is about the installation of microwave radiation, which uses a dipole lattice on the basis of a surface waveguide, located inside the reflector in the form of a specular parabolic conducting cylinder. Such dipole lattice will allow to obtain a uniform distribution of microwave energy over the area (surface).

When a single-wire transmission line is excited, the corresponding surface wave of the E_{00} -type electromagnetic field structure is established, containing the radial E_r and the longitudinal E_z electric field components, and the corresponding magnetic field component [4]. The lattice vibrators are made in the form of cylinders that are worn on the wire and installed on the wire along the longitudinal line of the electric field strength. The radial component of the field does not induce an electric current because the direction of the radial component of the electric field is perpendicular to the axis of the vibrator. Figure 1 shows a fragment of the location of three



longitudinal vibrators that are worn on the wire of a single-wire transmission line and are excited by the electric field of the E_{00} wave propagating in a single-wire transmission line.

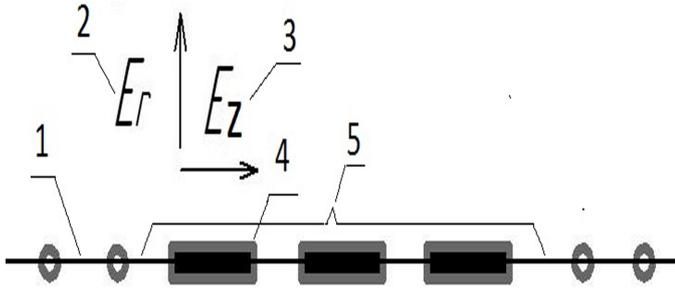


Fig. 1. The layout of the vibrators in the antenna array: 1 – a wire, 2 – a radial component of E_r , 3 – longitudinal component of E_z , 4 – the vibrator, 5 – an antenna lattice

Achieving a uniform distribution of superhigh-frequency energy to the surface is ensured by the fact that the dipole lattice, containing a single-wire transmission line of the surface wave with vibrators arranged coaxially with the wire, is located inside the specular parabolic conducting cylinder on the focal axis. In a section perpendicular to the focal axis, there is a parabola with a point of focus, therefore the distribution of the field radiated by the antenna array in the direction orthogonal to the axis of the array is close to uniform. On the Figure 2 a diagram of an installation based on a surface wave for drying an object is represented.

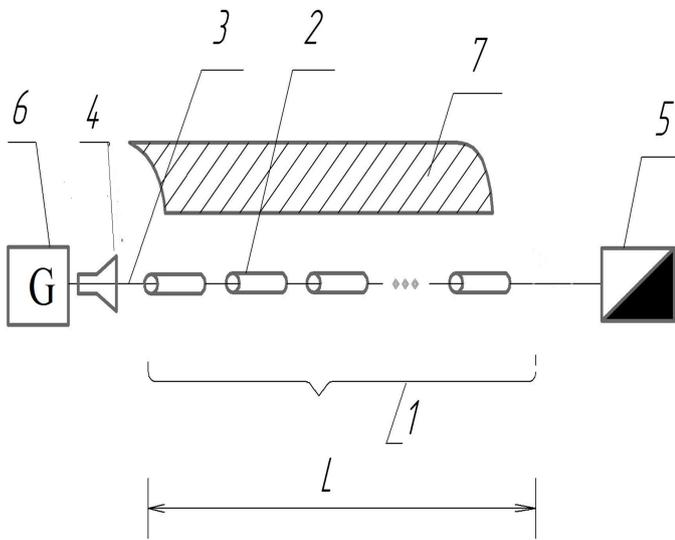


Fig. 2. Installation scheme based on surface wave for wood drying: 1 - dipole lattice 2 - vibrators, 3 - a wire of a single-wire transmission line with a dielectric covering, 4 - surface wave excitation system E_{00} , 5 - matched load, 6 - microwave signal generator, 7 - specular parabolic conducting cylinder

The collinear antenna lattice (1) is located inside the specular parabolic conducting cylinder (7). The antenna array included in the installation consists of identical vibrators (2), which are three-dimensional bodies with conductive cylindrical surfaces mounted on the dielectric surface of the wire (3) of a single-wire transmission

line terminates with a matched load (5). The microwave signal generator (6), located outside the mirror parabolic conducting cylinder, is connected to the surface wave excitation system (4).

Installation for the concentration of microwave energy at the drying facility operates as follows.

The signal from the generator of microwave oscillations (6) using the excitation device (4) excites the surface wave E_{00} in the wire (3). In the vibrators (2) on the wire of the antenna lattice (1), an electric current is induced by the longitudinal component of the electric field of E_{00} wave, as a result of which microwave energy is emitted. The radiation generated by the vibrators (2), propagating inside the volume of the parabolic cylinder (7), comes out in parallel with a beam of rays shown in Figure 3. All the unclaimed microwave energy goes into the load (5).

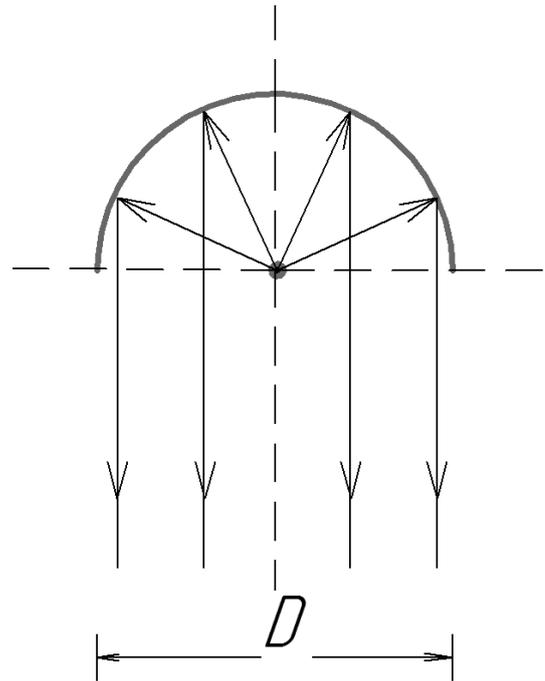


Fig. 3. Example of figure. Explain the significance of the figure in the caption.

Therefore, the energy per unit area of aperture of a mirror parabolic cylinder (energy density) will be identical. The degree of excitation of vibrators is determined by the coupling factor K_i of the surface wave from the calculation of achieving a uniform distribution along the length L of the energy distribution of the reradiated field T of the type carried out by the longitudinal component of the electric field strength:

$$K_i = \frac{P}{P_i}, \tag{1}$$

where P is the power of the microwave energy transferred by the surface wave; P_i is the power of microwave energy formed by the surface wave in the i -th vibrator of the considered collinear antenna lattice under the action of the longitudinal component of the electric field intensity [6].

The radiation of the collinear antenna array, propagating inside the mirror parabolic cylinder, is reflected from the

paraboloid surface and evenly concentrates on the aperture area of the parabolic cylinder S_p . Vibrators, being excited by the longitudinal component of the electric field strength of the surface wave E_{00} , further re-emit the electromagnetic energy of the T -structure. All the re-radiated microwave energy of the vibrator array is concentrated on the aperture area of the parabolic cylinder S_p , and the remaining (non-re-radiated) microwave energy enters the matched load.

Thus, the dipole lattice uniformly emits microwave energy along the entire length L of the collinear antenna array in the orthogonal single-wire transmission line of the plane, ensuring the concentration of the microwave radiation flux in the aperture area of the mirror parabolic cylinder S_p (Figure. 3).

$$S_p = D \cdot L, \quad (2)$$

where D – diameter of aperture of the specular parabolic conducting cylinder (reflector), L – length of a collinear antenna lattice.

The object for surface heating is placed in the installation in the area of concentration of microwave radiation flow. The advantages of the installation on the basis of the dipole lattice placed on a single-wire transmission line in the form of a single wire and ensuring the concentration of microwave energy on the surface (area) of the object are the following:

- the first, a uniform density distribution of microwave radiation is achieved in the aperture of the mirror parabolic conducting cylinder, which is caused by the placement of radiators on the focal axis of the collinear antenna array;
- the second, partial electrical closure of the volume of the mirror parabolic conducting cylinder provides partial shielding of the processes in objects inside the mirror parabolic cylinder;
- the third, there is an increase in the concentration of microwave energy on a given surface (area) S_0 ;
- the fourth, the minimum metal content and installation cost.

The proposed installation design can be used not only for drying wood in the woodworking industry, but also in agriculture, as well as for microwave heating of objects used in various industries.

III. ANALYSIS OF ENERGY CONSUMPTION FOR DRYING A SPECIFIED AMOUNT OF WOOD (SPRUCE)

Initially, we estimate the energy consumption for drying a given volume of a particular wood (spruce), which has a certain initial moisture content H_i , that must be brought to a final moisture content H_f within a certain time t . Considering the complex dependence of energy consumption on the amount of moisture in the dielectric constant, the tangent of the dielectric loss angle, and energy attenuation with depth, first it is necessary to restrict ourselves to solving a static problem. In the future, taking into account the features of the installation, we will make the appropriate adjustments.

Let us find a relationship between the input power P_0 , exposure time t and an initial moisture content of the wood

H_i . First of all, we determine the frequency of the generator, the type of wood, initial and final humidity.

So, the input power P_0 is supplied to a surface wave excitation device in a wire connected in a certain way to a collinear antenna array. Let us assume that a power loss is 5%. Given that most of the installation is shielded, it can be presumed that the losses are small and can be neglected. Then the power flow in the aperture of the parabolic cylinder will be:

$$|P_c| = \frac{0,95 \cdot P_0}{S_p}, \quad (3)$$

or

$$|P_c| = \frac{0,95 \cdot P_0}{D \cdot L}, \quad (4)$$

where D – an aperture of parabolas, L – length of an antenna lattice. The heated object has an area on which the flow $|P_c|$, equal to S_0 falls. Therefore the flow falls on an object $D \cdot L/S_p$ times less i.e.:

$$|P_c|_0 = \frac{0,95 \cdot P_0 \cdot S_0}{(D \cdot L)^2}, \quad (5)$$

The flow $|P_c|_0$ creates an intensity of electromagnetic field E in an object which is equal to:

$$\sqrt{|P_c|_0} = \sqrt{Z} \cdot E, \quad (6)$$

Z – the wave resistance of the irradiated object.

In the irradiated object the power will be allocated which is equal to:

$$P_d \approx \omega \cdot tg\delta \cdot V \cdot E^2, \quad (7)$$

where ω – the circular frequency, the V – is the object volume, ε – is relative dielectric constant, $tg\delta$ – a tangent of angle of dielectric processes, E – electric field intensity in an object, σ – specific conductivity.

The power released in an object leads to heat release of Q which is related to the heat capacity, the object mass m and the difference between initial and final heating temperature ΔT . Therefore the following equality takes place:

$$Q = \frac{P_d}{t}, \quad (8)$$

$$Q = c \cdot m \cdot \Delta T. \quad (9)$$

Thus, the equation (10):

$$0,95 \cdot P_0 \cdot Z \cdot \omega \cdot tg\delta \cdot \varepsilon \cdot V h \left(\frac{S_0}{S_p} \right)^2 = c \cdot m \cdot \Delta T \cdot t, \quad (10)$$

relates electrodynamic and physical parameters with energy and time of exposure. As for humidity, it is implicitly hidden in dielectric constant and a dielectric loss tangent of simple expressions.

The presented equation (10) is parametric since $tg\delta$, ε , Z depend on the expose time and nature of dependence cannot be

considered linear. The specified phenomena are to be further investigated in addition theoretically and experimentally.

As an example we calculate the required power of microwave generator P_0 for heating spruce wood at $\Delta T = 60^0C$, during time t , equal 4 hours. Oscillation frequency $f = 915$ MHz. The volume of wood is $V = (0,2 \times 0,9 \times 3)m^3$. Initial humidity of $H_i = 40\%$, final $H_f = 8\%$. Let us assume that relative dielectric constant of dry wood $\varepsilon = 4,2$, and wet $\varepsilon = (8 \div 10)$, respectively. The specific conductivity of dry wood $\sigma = 10^{-2}Cm/m$, and wet $\sigma = 10^{-3}Cm/m$. Specific heat capacity $c = 1.7kj/kgK$.

$$P_0 = A \cdot t, \quad (11)$$

where

$$A = \frac{c \cdot m \cdot \Delta T}{0,95 \cdot Z \cdot \omega \cdot tg\delta \cdot \varepsilon \cdot h \left(\frac{S_0}{S_p}\right)^2}, \quad (12)$$

where $\varepsilon \cdot \omega \cdot tg\delta \cdot h = \sigma$ - specific conductivity.

We calculate the wave resistance of the irradiated object Z

$$Z = \frac{Z_0}{\sqrt{\varepsilon}} = \frac{120\pi}{3} = 125Om. \quad (13)$$

$$P_0 \approx 10,5 \cdot 10^4 t. \quad (14)$$

Thus, when the heating time is 4 hours before reaching the mass of the object to the temperature difference $\Delta T = 60^0C$, $P_0 = 7,5$ kW will be required.

Further it will be required to evaporate moisture in quantity t defined by initial and final humidity. The heat of vaporization is determined by the formula:

$$Q_s = \lambda \cdot m. \quad (15)$$

Respectively, the required power of heating source is Q_s/t_1 . Since the heat release P_d is constantly maintained, the elapsed time is determined by the formulas:

$$t_1 = \frac{Q_s}{P_d}, \quad (16)$$

or

$$t_1 = \frac{Q_s}{\sigma \cdot h \left(\frac{S_0}{S_p}\right)^2 \cdot 0,95 \cdot P_0 \cdot Z}, \quad (17)$$

The carried-out above calculation shows that energy cost depends little on the method of drying implementation. However, there are reserves of energy savings. They are enclosed in the organization of the drying process according to a certain criterion, which is introduced into the system of automatic regulation of power and the time of completion of drying.

IV. SURFACE WAVE EXCITATION DEVICE E_{00}

The excitation devices can be built on the principle of creating components of electric and magnetic fields, providing the structure of the field of an open surface waveguide. For example, the classic coaxial horn at a certain length provides a smooth transition from the structure of the T wave to the E_{00} wave. This device is suggested by Goubau [7]. The classical scheme for the excitation of the surface wave E_{00} is shown in Figure 4.

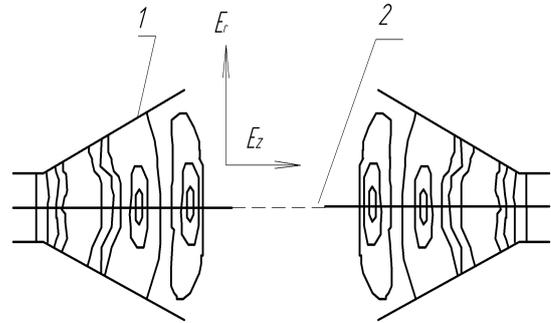


Fig. 4. The classical scheme of excitation of surface wave E_{00} : 1 - coaxial horn, 2 - a wire

Let us emphasize that the proposed coaxial horn is not used as an antenna, but solely as a transformer of the T -type field structure into the E_{00} wave. Note that Figure 4 shows only the components of the electric field for the E_{00} wave. The known disadvantages of such excitation devices are summarized as follows: the length of the horn exciter reaches two wavelengths; limited frequency range. In addition, the required tension of the wire of the surface waveguide is directly connected through soldering to the short-circuited wall of the horn coaxial. Such a connection does not provide a reliable contact.

We propose to eliminate these drawbacks with the help of the developed surface excitation system E_{00} . This system is shown in Figure 5.

The dipole system of excitation consists of three half-wave vibrators (1), (2), (3), one of which is connected to the coaxial feeder through quarter-wave the locking cup (4). The "star" system (5) formed of three half-wave vibrators is installed near the waveguide wire (6). On the one hand such system can be equipped with a reflector in the form of a disk (7), while electric closure of reflector with a wire is carried out through an open quarter-wave segment. The reflector is a conducting disk with a diameter of $d = 3x$, where x is boundary radius $x = 0,35m$.

Such dipole excitation device in general forms two surface waves E_{00} diverging along the z axes.

We conducted researches on the installation represented in Figure 6.

The installation shown in Figure 6 consists of a wire (1) with a dielectric coating of "fluoroplast-4" stretched relatively to two supports. The quarter-wave segments of the coaxial line formed by the tube and the waveguide wire were used as shorting connectors (3). These tubes were galvanically connected at one end to a reflector (2) in the form of a circular

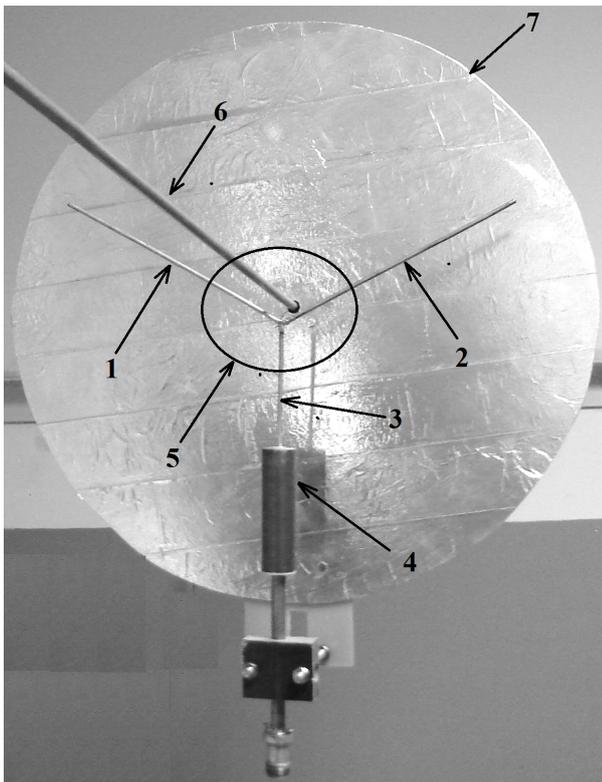


Fig. 5. Vibratory excitation system of the surface wave E_{00} : 1,2,3 – half-wave vibrators, 4 – quarter wave the locking cup, 5 – “star”, 6 – a wire, 7 – a reflector in the form of a disk

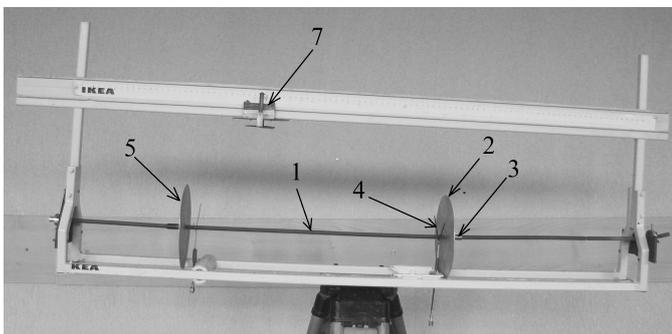


Fig. 6. View of experimental setup: 1 – a wire, 2 – reflector (reflector), 3 – a shorting connector, 4 – the system of excitement of a surface wave E_{00} “Star”, 5 – the reflector (reflector), 6 – the probe in the form of a dipole

conductive disk, and a “Star” (4) formed by exciting half-wave vibrators, which was connected to a generator. At the opposite end of the line there was a ballast load attached.

Thus, the study subject was a segment of insulated wire with reemitters, along which two parallel reflectors that could freely move without galvanic connection with the wire.

The following experiment was performed: a carriage with a probe in the form of a dipole (6) was moved along the wire (1), from which a signal to the receiver was taken. The probe had an ability for installation taking into account the polarization and minimal impact on the structure of the surface wave field E_{00} .

The results of measurements of the field distribution along the wire are shown in Figure 7.

The measurement results in the open resonator mode are displayed by a blue line. The measurement results of the loaded waveguide are displayed in red line.

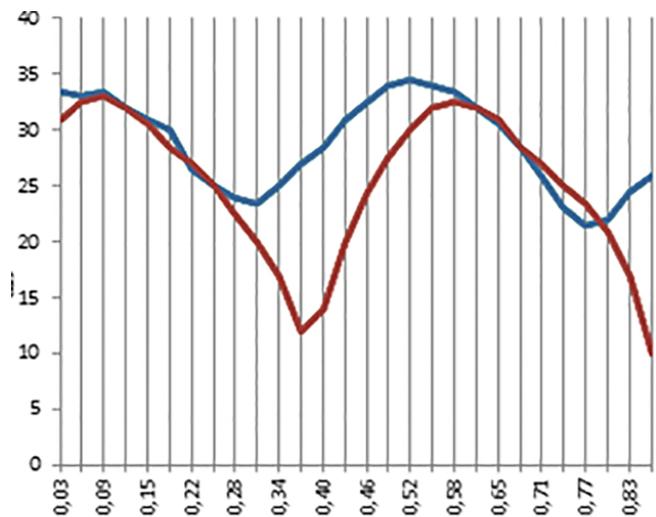


Fig. 7. The measurement results of the distribution of the field along the wire

As can be seen from the presented curves, in the case of the line mode as an open resonator, there is a clear distribution of the field according to the law of a sinusoid with pronounced minima and maxima. The difference between the maximum and minimum is about 20 dB.

The distance between the minima in wavelengths is close to half the wavelength (0.16 m), which indicates not only the presence of a surface wave along the wire, but also the corresponding position of the reflector, which provided an open resonator mode. As for the loaded waveguide mode, this mode is although far from the matched one, at the same time, the difference in the maximum and minimum values is small and is about (5 ÷ 6) dB. A characteristic is the presence of a wave process with a wavelength (0.327 m) which is close to the calculated wavelength in a line (0.326 m).

A feature of the described experiment is the indication of the electric field intensity in the area of the surface wave structure, that is within the boundary radius (the probe (6) for fixing the signal is located no further than 0.16 m from the line). In this case, the radiation is minimal and the measurement setup does not require special measures to eliminate the influence beyond the boundary radius.

Such a dipole excitation system allows solving a number of important practical problems. Among them, non-contact method of excitation, extended frequency band, the possibility of excitation at any point of the wire, the ability to install a reflector, etc.

V. BALLAST LOAD

The next stage of the research is a creation of a ballast load design that is meant to absorb the components of the electromagnetic field of the E_{00} wave.

The ballast load for the above dipole excitation system, in the simplest case, can be realized by installing a conventional reflector in the form of a conducting disk at its end. In general, this design is quite complicated. In this regard, variants of loads that are directly worn on the waveguide wire are of interest. The principle of operation of such loads consists in placing absorbing materials in the plane of oscillations of intensity vector of the electric field. Judging by the structure of the electromagnetic field of a surface wave near a wire with a surface wave, there are two such components. One of them is the radial component E_r , the second is the longitudinal E_z , directed along the propagation of the surface wave and coinciding with the direction of the wire axis. According to it the designs of ballast loads are being projected.

The study of loads calculated for the absorption of the longitudinal component of the electric field was carried out on a structure in the form of a composite sleeve, canted along the z axis and worn on the wire Figure 8.

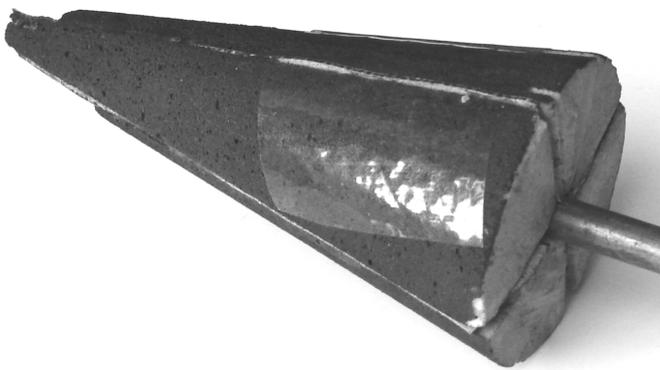


Fig. 8. Option design of ballast load

A very simple design and volume of the composite at the frequencies of 2400 MHz and even 915 MHz is acceptable. Moreover, this design achieves a relatively high agreement.

VI. CONCLUSION

As a result of the conducted research the opportunities for the implementation of microwave irradiating installation were predetermined, in which:

- in the open resonator mode a significant increase in the reemitted level of the electric field intensity is possible;
- in the open resonator mode the contactless adjustment of the reradiated field level is possible;
- the distribution of the re-emitted field is determined by the electromagnetic coupling of the reradiator with the field of the surface waveguide;

This work is an important step in laying the road to the microwave drying industry of wood processing enterprises.

Continuing work in the direction of microwave drying wood will give a significant impetus to the development of woodworking. Also this type of development entails the development of other areas of industry, in particular, dielectric heating of bitumen masses, ceramic products, medicinal herbs, cereals, etc.

REFERENCES

- [1] T. Grigory, and P. Vinden, High-intensity microwave wood modification for increasing permeability. *Forest Product Journal*, 2009, 59(4), pp. 84-92.
- [2] M. Leiker, and M. Adamska, Energy efficiency and drying rates during vacuum microwave drying of Wood. 2004, pp. 203-208.
- [3] P. Perre, I. Turner, Microwave drying of softwood in an oversized waveguide. Theory and experiment. *AIChE Journal* 1997, 43 (10), 2578-2579.
- [4] Idris Ahmed Ali, Effect of load on the heating efficiency and temperature uniformity in multimode cavity applicators, *Journal of microwave power and electromagnetic energy*. 2016.vol.50, pp.123-137.
- [5] P. Ziclonka, E. Gicrlík, Temperature distribution during conventional and microwave wood heating. *Holz als Roh und Werkstoff* 1999. 57, pp.247-249.
- [6] A. Antti, H. Zhao, I. Turner, An investigation of the heating of wood in an industrial microwave applicator: Theory and practice. *Drying Technology* 2000. 18 (8), pp.1665-1676.
- [7] Goubau G. Surface waves and their application to transmission lines. *Journal of Applied Physics*. 1950.vol.21, pp.1119-1128.
- [8] Chicone C., Feng Z.C.. Synchronization phenomena for coupled delay-line oscillators. *Physica*, 2004, pp.212-230.
- [9] M. Inoue, Y. Yamamoto, Application of Dielectric Heating by a Microwave=High Frequency in Wood Industry, Tokyo, Japan, 2004.
- [10] M. Moller, H. Linn, Microwave drying of refractory materials. *Refractories Special Issues* 2001,5, pp.79-80
- [11] G. Torgovnikov and P. Vinden, High-intensity microwave wood modification for increasing permeability, *Forest Products Journal*, 2009 59 (4), pp.84-92.
- [12] A. Herritsch, J. Dronfield, J.Nijdam, Intermittent and continuous drying of red beech timber from the green condition. *Drying Technology* 2010, 28, pp.269-277.
- [13] Dharmendra Singh Rajpurohit and Rahul Chhibber, Design of Multimode Microwave Cavity for Materials Processing, 5th International 26th India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12th- 14th. 2014. Guwahati, Assam. India.