A new type of non-thermal atmospheric pressure plasma source based on a waveguide bridge

V N Tikhonov\textsuperscript{1,2}, S A Gorbatov\textsuperscript{1}, I A Ivanov\textsuperscript{1,2} and A V Tikhonov\textsuperscript{1}

\textsuperscript{1}Russian Institute of Radiology and Agroecology, Kiev highway 109th km, Obninsk, 249032, Russia
\textsuperscript{2}Scientific and production enterprise "Agroecoteh" LLC, Kiev highway 109th km, Obninsk, 249032, Russia

E-mail: v.n.tihonov@yandex.ru

Abstract. A new type of microwave source of non-thermal atmospheric pressure plasmas, presented earlier by the authors, has both the characteristics of a dielectric barrier discharge (in terms of the configuration and low gas temperature) and an ability to form a "clean" plasma jet like a classical microwave plasma torch. However, the need to use a circulator leads to a significant increase in complexity, cost and weight of the installation as a whole. The basis of the presented plasma source is a three-decibel waveguide bridge with connection through a narrow wall. Both output arms of the bridge are loaded on identical short-circuited segments of waveguides. The discharge tube passes across the waveguides at a distance of a quarter of the wavelength from the short circuit. Since the output arms of the bridge are always loaded symmetrically, the generator's power which is reflected from the short circuits or not absorbed in the microwave discharge, enters the decoupled arm of the bridge that is connected to the matched load. Thus, the magnetron is protected from the reflected wave without the need for an expensive circulator, in any case.

1. Introduction
Non-equilibrium non-thermal plasma can be obtained quite simply at a reduced pressure about 10-15\% of atmosphere, and its widespread use began in the 1970s in the then rapidly developing computer industry, in particular, plasma etching of semiconductor materials in the manufacture of microcircuits [1]. Since the 90s of the 20th century, advances in the development of technologies for producing Non-Thermal Atmospheric pressure Plasma (NTAP) have eliminated the need for expensive vacuum chambers and pumping systems. As a result, non-thermal plasma applications such as plasma medicine, agriculture, water purification, food safety and others have appeared [2]. In recent years, interest in non-equilibrium discharges at atmospheric pressure has increased greatly, and the field of application of such discharges has been growing continuously [3, 4].

For these purposes, low-current discharges - corona and dielectric barrier discharges (DBD), which have a limited efficiency of gas activation, were initially used as sources of non-equilibrium atmospheric pressure plasma of non-destructive action. The microwave discharge of atmospheric pressure removes the restrictions of the specific power. However, the microwave plasmatron of the classical electrodeless "surfatron" design, forms a plasma jet with a temperature of several thousand degrees or more at atmospheric pressure.
Recently developed electrode microwave dischargers [5-7] form argon plasma with a temperature of tens of degrees Celsius, but such a plasma may contain products of destruction of the electrode material. It is a result of significant overheating of the electrodes, which sharply limits the permissible level of the invested microwave power.

The new type of microwave NTAP source, presented in [8], possesses both the features of DBD (in terms of configuration and low gas temperature) and the ability to form a "clean" plasma jet similar to the classical microwave plasmatron. The microwave discharge is excited in a dielectric tube passing across the waveguide, perpendicular to the electric field strength vector E. In this configuration, two wide walls of the waveguide can be considered as an electrode system of two flat parallel electrodes located in parallel to the axis of the discharge tube, which walls play the role of a dielectric barrier. This gives us reason to use the term Microwave Barrier Discharge (MBD) hereinafter.

2. Problem formulation

The aforementioned configuration of a non-thermal plasma MBD source can be implemented on the basis of waveguide concentrators of the electromagnetic field strength in two ways - a resonant console or a broadband pass-through. These two options differ in the way of connecting the device to the microwave generator and each of them has its own advantages and disadvantages.

Let’s take a closer look.

2.1. Resonant device of the "platypus" type

The design of the resonant source of the MBD plasma is a segment of a rectangular waveguide, operating on the basic type of oscillations $H_{10}$, that is short-circuited at the end and strongly diaphragmed at the beginning. The length of the segment was chosen close to the resonant one. A discharge tube is placed across the waveguide so, that its axis is perpendicular to the electric field vector in the antinode of the standing wave, which closest to the short-circuited end of the waveguide. The height of the waveguide in this zone is significantly reduced to increase the electric field strength.

The image of this device and the scheme of its connection to a microwave generator are shown in the figure 1.

![Figure 1. Resonant device of the "platypus" type (left) and his connection diagram (right) – (explanations in the text).](image-url)
unused part of the energy returned to the untied arm C of the Circulator and absorbed in the matched load L.

The main disadvantage of the resonant MBD-plasma source is the necessity to include an expensive and bulky circulator in the waveguide path – in order to protect the magnetron from a significant reflected wave. In addition, the permissible level of the microwave power supplied to the concentrator in the range of 2.45 GHz is limited to the value of about 200-300 W. This is caused by a massive E-field strength in the absence of a discharge, which leads to air breakdowns in the waveguide outside the discharge tube. To maintain resonant discharge conditions, additional technical solutions are required, which greatly complicate the design of the device.

2.2. A pass-through MBD-plasma source
The pass-through non-resonant MBD-plasma source shown in the figure 2 does not require a circulator for its operation, since the microwave generator G is always loaded to a matched load L here.

![Figure 2. The pass-through device (left) and his connection diagram (right).](image)

The permissible (by breakdown) level of microwave power supplied to the plasma source is much higher here than in a resonant concentrator, but the need for significant thinning of the waveguide greatly limits the diameter of the discharge tube. In addition, the conditions for initiation and maintenance of the discharge are deteriorated, and the small size of the plasma leads to the fact that the efficiency of the deposition of microwave power passing through the waveguide into the discharge is very low, and a significant part of it is lost in the matched load.

3. Technical description
The main idea is to replace the circulator used in the console configuration (figure 1) with a three-decibel H-plane waveguide bridge, which has a connection through a narrow wall (figure 3).

![Figure 3. Diagram representing the main idea of this publication (explanations are in the text).](image)
A three-decibel waveguide bridge divides the microwave power coming from the generator G into the input arm of the bridge A, strictly in half between its two output arms B and D. Its unique property is that if both output arms of such a bridge are loaded on any arbitrary but identical loads, then all the power reflected from them will go to the fourth, "untied" arm C of the bridge. By connecting the matched load L to the untied arm C, we will save the microwave generator G from troubles, even in the case of very significant reflections.

3.1. Construction design and optimization of the calculation model
We used the rich capabilities of the Ansys High Frequency Structure Simulator (HFSS) software package, which allows performing electrodynamic modeling of microwave structures using the finite element method to calculate the geometric parameters of the waveguide bridge and their subsequent optimization. A longitudinal section in H-plane of the calculated model of the electromagnetic structure is shown in the figure 4. The arrangement of the main elements of the circuit corresponds to those shown in the figure 3.

![Figure 4. Section of an optimized model of the electrodynamics structure of a three-decibel waveguide H-bridge.](image)

A multi-stage optimization of the geometric parameters of the H-bridge (mainly the dimensions of the communication window) was initially performed for the case of connecting matched loads to the output arms B and D of the bridge. As optimization criteria, the condition of dividing the power transmitted to the arms B and D strictly in half, as well as the minimum reflections from the input arm A, was used. The width of the waveguides was assumed to be 90 mm, and the optimal height turned out to be close to 20 mm as a result of optimization. At the second stage of parametric optimization, a digital model of a bridge with short-circuited segments in the arms B and D was studied.

It is interesting to note the following here. It turned out that depending on the length of the short-circuited segments, the operating mode of such an H-bridge, changes significantly. This is clearly seen in the figure 4, where the diagrams of the distribution of the complex amplitude of the E-field for the two extreme cases are presented. As we can see, the situation presented in the figure 4 right is the most suitable for solving our problem.

3.2. Design, manufacture, and testing of the demonstrator model
An experimental model of an MBD-source of non-thermal plasma was developed and manufactured based on the calculated geometric parameters of the waveguide H-bridge (figure 5).

The bends of the waveguides in the bridge arms, which are necessary for the implementation of the assembly conditions of the device, perform the function of smooth matching transitions to the standard section of the waveguides (90×45 mm) simultaneously.
Main problems that bothered us throughout the entire time of solving this problem were the following. Will the necessary phase and amplitude ratios in the output arms B and D of the H-bridge be preserved in the case of a strong electromagnetic connection between them through a common plasma jet? How will the entire device work if the discharge excitation occurs only in one of the arms? Only a direct experiment could give us an answer to these questions. And the answer was received.

![An experimental model of a 3-dB waveguide H-bridge.](image1)

**Figure 5.** An experimental model of a 3-dB waveguide H-bridge.

The figure 6 shows the operating moment of fire tests of a non-thermal MBD-plasma source based on a three-decibel waveguide H-bridge.

![A non-thermal MBD-plasma source based on a three-decibel waveguide H-bridge.](image2)

**Figure 6.** A non-thermal MBD-plasma source based on a three-decibel waveguide H-bridge.

### 4. Conclusions
Calculations and optimization of the parameters of the electromagnetic system of the proposed model of a non-thermal MBD plasma source were carried out using the HFSS software package and were implemented in the developed and manufactured experimental model. The tests confidently confirmed the possibility of creating an inexpensive microwave NTAP-source based on a three-decibel waveguide bridge without the need for a complex and expensive circulator to protect the magnetron from possible reflections of microwave energy.
It is especially important to note that in the presented design, the height of the waveguide and, accordingly, the diameter of the discharge tube can be significantly larger than in the E-concentrators described above. Thus, in the presented sample of the MBD source of the NTAP, the height of the waveguides in the discharge formation zone is 20 mm compared to 8 and 10 mm in the E-concentrators. Therefore, the cross-sectional area of the discharge tube and the formed plasma jet can be increased fourfold. In addition, the power supplied to the H-bridge and introduced into the microwave discharge can also be significantly increased.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (project No. 20-08-00894).

References
[1] Lebedev Yu 2015 Plasma Sources Sci. T. 24 053001
[2] Nehra V, Kumar A and Dwivedi H K 2008 International Journal of Engineering 2 53-68
[3] Misra N N, Schlüter O and Cullen P J 2016 Cold plasma in food and agriculture: fundamentals and applications (London: Academic Press)
[4] Laroussi M, Nie L L and Lu X 2020 Plasma Cancer Therapy. Springer Series on Atomic, Optical, and Plasma Physics vol 115 (Cham: Springer) pp 15–51
[5] Morfill G, Simizu T, Shteffes B and Fudzii S 2006 Plazmennyy istochnik (Plasma source). Patent RF no. 2415522
[6] Adtec Europe Limited: Adtec SteriPlas – Third generation device for general clinical use http://www.adtecplasma.com/
[7] Tikhonov V N, Aleshin S N, Ivanov I A and Tikhonov A V 2017 J. Phys. Conf. Ser. 927 012067
[8] Tikhonov V N, Ivanov I A and Tikhonov A V 2019 J. Phys. Conf. Ser. 1393 012062