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PLASMA TORCH USING A WAVEGUIDE BRIDGE AT A FREQUENCY OF 2.45 GHz

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This paper describes an atmospheric-pressure plasma microwave system operating at a frequency of 2.45 GHz. To protect the magnetron generator from parasitic reflections, a waveguide bridge with a connection via the wide wall of the waveguide is used instead of a complex and expensive ferrite circulator. The bridge is based on a waveguide with a cross-section of 90x20 mm. The design was optimized using CST Microwave Studio. Simulation showed that the design provides a return loss at the input of -43 dB at a frequency of 2.45 GHz. In the frequency band from 2.3 to 2.6 GHz, the voltage standing wave ratio (VSWR) does not exceed 1.2. Successful "fire" tests have been carried out in a stream of atmospheric air.

INTRODUCTION

In recent decades, there has been growing interest in research involving non-equilibrium plasma, generated by microwave discharges. The unique properties of such plasma have led to its widespread application in promising fields of science, medicine, industry and agriculture [1, 2].

To date, a vast number of plasmatron designs have been developed for a wide variety of applications. Numerous specialist firms offer their products on the market. One can find both powerful, large-scale devices for industrial or environmental applications [3], and comparatively small laboratory-scale devices for scientific research, operating at a frequency of 2.45 GHz [4, 5]. And the need for the development of reliable, simple to manufacture and inexpensive plasma-based microwave systems is only growing.

Currently, two approaches to the creation of such systems have emerged.

The first approach involves using the necessary components, manufactured by specialist firms, with certain specific modifications when integrating them into a particular system. This approach is typically implemented by large specialist firms, such as Sairem (France) [6] or Omicron Scientific Equipment CO (India) [7]. As a rule, expensive and complex ferrite circulators are used in such systems to protect the microwave generator.

The second approach involves using the most readily available, relatively inexpensive microwave generators and power supplies on the market, whilst having the plasma torch units themselves custom-built for specific tasks by scientific laboratories and research groups. This approach has become feasible thanks to the widespread use of domestic microwave ovens, which, as is well known, operate at a frequency of (2450±50) MHz. Mass production and fierce competition among leading manufacturers in the global market ensure high reliability of their products at a low cost. The need for repair and maintenance of a vast fleet of microwave ovens also ensures that spare parts for them are cheap and readily available.

The first, "classical", approach is illustrated in Fig. 1 [4]. In the simplest case, microwave plasmatron consists of a rectangular waveguide on an H_{10} wave mode and a dielectric discharge tube passing through the middle of its wide wall. According to the "classic" configuration for incorporating such a plasmatron into a plasma complex, a movable or fixed short-circuiting piston is placed after discharge tube (see Fig. 1).

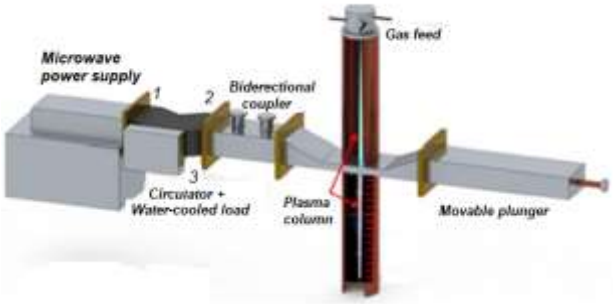


Fig. 1. An example of a standard plasmatron connection diagram

However, it is necessary to effectively protect the magnetron from reflected waves in the plasma absence case. In Fig. 1, the microwave energy from the magnetron generator feeds the plasma jet in the discharge tube of the plasma torch through the arms *1* and *2* of the circulator. The reflected and unused part of the energy returned to the lateral arm *3* of the circulator and absorbed in the matched load.

There is a circuit in which the waveguide following the discharge tube is connected to a matched load, thereby protecting the magnetron generator without the use of a circulator. However, this results in poorer conditions for initiating and sustaining the microwave discharge.

1. DESCRIPTION OF THE PLASMATRON DESIGN

The main idea is to develop a plasmatron that does not require the use of a ferrite circulator to protect the microwave generator and does not compromise the performance of the circuit compared to the conventional design. This was achieved by constructing a plasmatron

using a three-decibel waveguide bridge. Such a bridge divides the power entering its input arm strictly in half between its two output arms. 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 of the bridge. By connecting the matched load to the untied arm, we will protect the microwave generator from damage, even in the case of very significant reflections. This property of waveguide bridges has long been known and is widely used in the construction of phase shifters and antenna switches.

We used a variant of a waveguide bridge with coupling via the wide walls of the waveguides (a so-called *E*-bridge). The height of each waveguide was reduced to 20 mm with a waveguide width of 90 mm, and two longitudinal connection slots, 20 mm wide, are provided near the side (narrow) walls of the waveguides (Fig. 2).

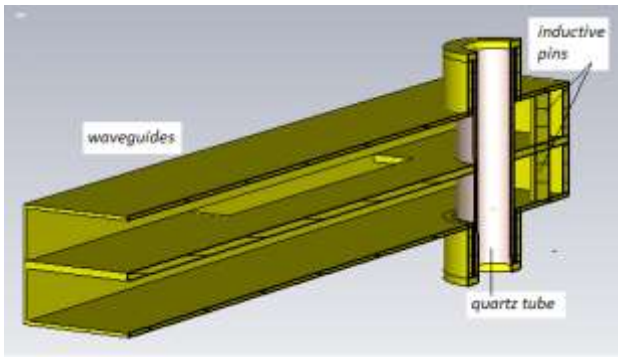


Fig. 2. Longitudinal section of a plasma torch model

At a distance of 23 mm from the ends of the coupling slots, 30 mm diameter holes are drilled in the centre of the wide walls and perpendicular to them, into which a quartz glass discharge tube is inserted. Behind the discharge tube, tuning inductive pins with a diameter of 10 mm are installed in the waveguides; these essentially replace the bulky reflecting pistons across the entire cross-section of the waveguides. The pins slide along the wide walls of the waveguide on spring-loaded "slides", ensuring smooth movement via special rods whilst maintaining good electrical contact. The distance from the centre of the tube to the centers of the inductive pins was initially set equal to a quarter of the wavelength in the waveguide and was refined during the optimization process, and subsequently during the device's tuning.

As can be clearly seen from Fig. 2, the plasmatron itself (the section of waveguide containing the tube) and the waveguide bridge form a single unit, and the simplified analysis that was suitable for describing, for example, a phase shifter, is no longer appropriate.

2. COMPUTER SIMULATION OF A PLASMATRON

The simulation was carried out using CST Microwave Studio and took place in several stages. First, a model of a "pure" waveguide bridge was examined, featuring longitudinal connection slots through the wide walls of waveguides with a cross-section of 90x20 mm. Fig. 2 shows the part of the structure bounded by the section without additional structural elements beyond the connection slots.

Fig. 3 shows the electromagnetic field formed inside the bridge. In this case, outputs *2* and *3* are subjected to matched loads. The cross-section uses a color-coded scale to indicate the magnitude of the complex amplitude of the electric component of the electromagnetic field.

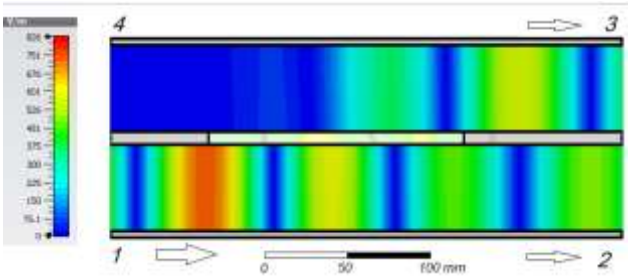


Fig. 3. Longitudinal section of the waveguide bridge computation model

Simulations have shown that a travelling-wave mode has been established throughout the device, with the wave propagating from arm *1* to arms *2* and *3*. Consequently, the field strength in the input arm *1* is at its maximum (red), whilst in the output arm *4* it is close to zero (blue). In arms *2* and *3*, the power is split equally, with the field in arm *3* (upper waveguide) leading the field in arm *2* (lower waveguide) by 90^0 in phase. The calculation also showed that at the input waveguide the reflection coefficient is -54 dB, which corresponds to a VSWR of no more than 1.05 at a frequency of 2.45 GHz. This stage of the calculations made it possible to determine the optimal length of the coupling slots for a frequency of 2.45 GHz, which was 150 mm.

This idyllic picture begins to unravel when the necessary design modifications are made to the model. For instance, the 30 mm diameter hole between the waveguides significantly increases the reflection coefficient at input *1* to level -23 dB, which, however, cannot be considered as poor result. It should be noted that, following the introduction of the gap, the length of the coupling slots had to be adjusted (to 144 from the original 150 mm). Placing the quartz discharge tube with an external diameter of 30 mm and an internal diameter of 25 mm in its "standard" position, led to virtually no further change in the parameters.

The most significant changes occurred following the installation of inductive pins in arms 2 and 3. This manifested itself in the appearance of deep (-55 dB) resonance minima (dips) in the frequency dependence of the reflection coefficient in arm 1 at frequencies both below and above 2.45 GHz. The position of the minima can be controlled by moving the pins along the waveguide axis and changing the slot length. This results in a "two-dip" VSWR characteristic with an extended operating band. Following simulation, we settled on a slot length of 135 mm and a distance of 44 mm from the centre of the discharge tube to the inductive pins, which is very close to a quarter of the microwave signal wavelength in the waveguide (42 mm). This made it possible to achieve an operating band for the device from 2.3 to 2.6 GHz (approximately 300 MHz) with a VSWR of 1.2.

Such a wide bandwidth may seem excessive in our case, since the permissible frequency deviation of microwave oven magnetron generators is no more than ±50 MHz. However, as practice has shown, this made it possible to dispense with any fine-tuning during the transition from "cold" mode to discharge ignition mode.

Fig. 4 shows the electromagnetic field distribution in the full version of the computational model.

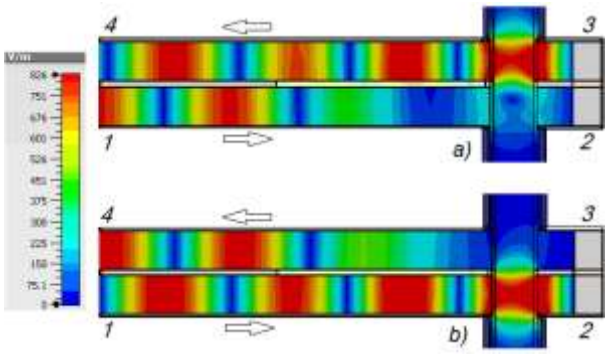


Fig. 4. Longitudinal section of the full version of the plasmatron computational model

The analysis shows that the travelling wave at input *1* propagates to the right in the figure, whilst at output *4* the travelling wave propagates to the left. A pure standing wave is observed in the vicinity of the discharge tube. Fig. 4 correspond to a 90° phase shift of the field, which corresponds to a time shift of a quarter of the signals microwave period. It can be seen that when the highest field intensity is observed in the upper waveguide (arm *3*), a field minimum is observed in the lower waveguide (arm *2*), and vice versa. As a result of this effect, the interaction between the electromagnetic fields in arms *2* and *3* via the common plasma jet is weakened, and the phase relationship between the arms remains undistorted during discharge. Dynamically, the field appears to "jump" from one waveguide to the other. Due to its inertial properties, the gas discharge plasma perceives such a field as being "smeared" across the two waveguides.

The calculated VSWR at the input to the bridge (arm *1*) for frequency of 2.45 GHz is 1.1, and does not exceed 1.2 within the (2450±150) MHz frequency band. These parameters undoubtedly ensure the safe operation of the magnetron generator with this type of plasma torch.

3. DESIGN, MANUFACTURE AND TESTING OF THE EXPERIMENTAL MODEL

Fig. 5 shows the final version of the computer model of the plasmatron. It has been fitted with *H*-plane elbow and flanges to ensure compatibility with other components of the microwave complex.

A working experimental model of the device has been constructed based on the dimensions of the calculated model. The device components are made from 1.5 mm thick copper sheet bent on suitable mandrels and joined by soldering. Adapters in the form of quarter-wave transformers have been specially designed and manufactured to connect arms *1* and *4*, which have a reduced height, to waveguide elements of standard cross-section.

Circular evanescent-waveguide sections are attached to the apertures in the waveguides used for insertion of the discharge tube. This is done to suppress microwave radiation in the absence of a plasma discharge.

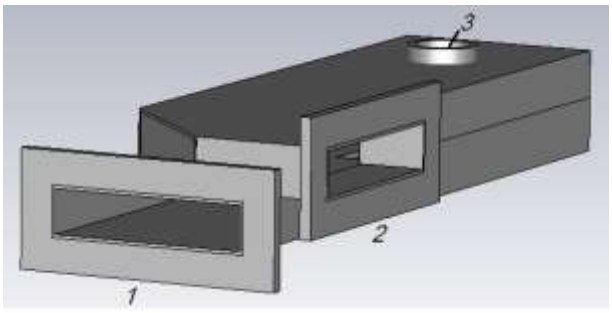


Fig. 5. Computer model of a plasmatron: 1 – input arm; 2 – output arm; 3 – opening for the discharge tube

We did not optimize the gas supply system to the plasma torch. The simplest swirl generator was used, consisting of two tangential inlets for the working gas (in particular, air).

Fig. 6 shows a photograph of the experimental setup assembled for testing the plasmatron.

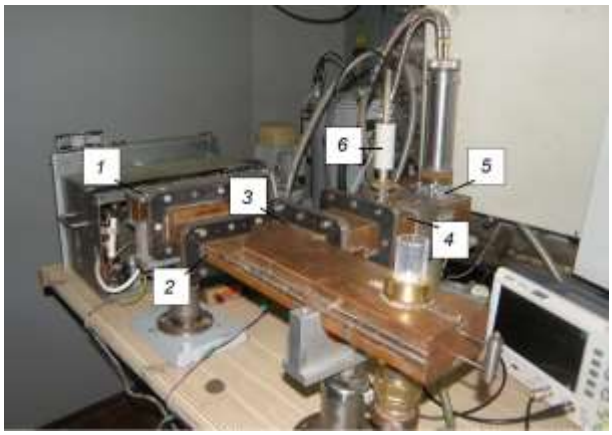


Fig. 6. Photograph of the experimental setup: 1 – microwave generator; 2 – input arm; 3 – output arm; 4 – waveguide-coaxial splitter; 5 – water matched load; 6 – microwave detector

The signal from the microwave generator *1* is fed via an adapter into the input (lower in the photography) arm *2* of the plasma torch. The output (upper) arm *3* is connected via a second adapter and a waveguide-coaxial splitter *4* to a water-matched load *5*, which we developed previously [8]. The waveguide-coaxial unidirectional coupler has a coupling factor of -33 dB and is designed to monitor the power passing through the waveguides.

A microwave detector is connected to the coaxial arm of the splitter; the signal from this detector is proportional to the power delivered to the load. With appropriate calibration, the power absorbed by the gas discharge plasma can be estimated from the detector signal.

Before initiating the discharge, it is necessary to adjust the position of the field amplitude peak relative to the centre of the discharge tube. For this purpose, a small probe was fabricated using the microwave detector as a base. Probe was temporarily inserted into the

centre of the tube. The insertion depth was selected based on the signal level from the microwave detector, sufficient for reliable detection. The maximum signal from the detector was then achieved using movable rods.

Fig. 7 shows photographs of the microwave discharge (flame) observed during the tests. Air is used as the working gas. The different shapes of the flame in the photographs are due to the varying gas flow rates of 5, 20, and 50 l/min, respectively. Flame height in the case shown in Fig. 7,a reaches 150 mm.

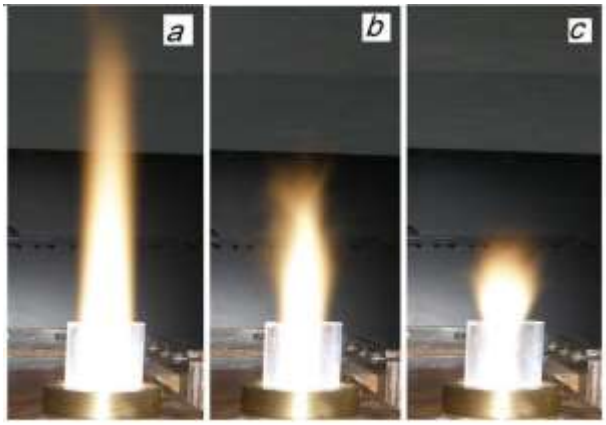


Fig. 7. Plasma discharge at different gas flow rates: 5 l/min (a); 20 l/min (b); 50 l/min (c)

The discharge is initiated by briefly placing a burning splinter into the discharge tube whilst the microwave generator is switched on. This unconventional method arose from an attempt to demonstrate a "trick" to staff, whereby a match placed briefly into the discharge tube would flare up. The match did indeed ignite, and at the same time, a plasma discharge was initiated. It later turned out that matches were not necessary to initiate the discharge, a burning wood splinter was sufficient. In fact, even a smoldering ember at its tip was enough. The literature describes other methods of initiating a discharge, most of which are also suitable in our case.

It should be noted that the discharge burns steadily over a wide range of air flow rates, from 3 to 100 l/min. However, when the flow rate is low, the system overheats quickly.

The main advantages of the developed design are its simplicity, low cost and reliability.

CONCLUSIONS

Calculations and optimizations of the electromagnetic system parameters for the proposed plasmatron model, using the capabilities of CST Microwave Studio, enabled us to design and fabricate an experimental prototype of the device.

Tests have conclusively confirmed the feasibility of creating an inexpensive plasma complex using a waveguide bridge, eliminating the need for an expensive ferrite circulator to protect the magnetron from parasitic reflections of microwave energy.

This plasmatron may be useful in experimental studies of the interaction of microwave plasma with various substances in plasma chemical technologies across various fields.

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ПЛАЗМОТРОН ІЗ ВИКОРИСТАННЯМ ХВИЛЕВОДНОГО МОСТА НА ЧАСТОТУ 2,45 ГГц

А.Г. Нагорний, С.О. Єрьомін, Д.А. Нагорний, О.Ю. Роєнко

Описано плазмовий надвисокочастотний комплекс атмосферного тиску, що працює на частоті 2,45 ГГц, у якому для захисту магнетронного генератора від паразитних відбиттів замість складного й дорогого феритового циркулятора використано квадратурний міст із зв'язком через широку стінку хвилеводу. Міст створено на основі хвилеводу перерізом 90х20 мм. Оптимізація конструкції виконана за допомогою програми CST Microwave Studio. Моделювання показало, що конструкція забезпечує зворотне відбиття на вході на рівні -43 дБ при частоті 2,45 ГГц. У діапазоні частот 2,3...2,6 ГГц коефіцієнт стоячої хвилі за напругою (КСХН) не перевищує 1,2. Проведено успішні «вогневі» випробування на потоці атмосферного повітря.