The low-cost microwave plasma sources for science and industry applications

V N Tikhonov\(^1\), S N Aleshin\(^1\), I A Ivanov\(^1,2\) and A V Tikhonov\(^1\)

\(^1\) Russian Institute of Radiology and Agroecology, Kievskoe shosse, 109th km, Obninsk, Kaluga region, 249032, Russian Federation
\(^2\) Scientific and production enterprise "Agroecoteh" LLC, Kievskoe shosse, 109th km, Obninsk, Kaluga region, 249032, Russian Federation

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

Abstract. Microwave plasma torches proposed in the world market are built according to a scheme that can be called classical: power supply – magnetron head – microwave isolator with water load – reflected power meter – matching device – actual plasma torch – sliding short circuit. The total cost of devices from this list with a microwave generator of 3 kW in the performance, for example, of SAIREM (France), is about 17,000 €. We have changed the classical scheme of the microwave plasmathrone and optimised design of the waveguide channel. As a result, we can supply simple and reliable sources of microwave plasma (complete with our low-budget microwave generator up to 3 kW and a simple plasmathrone of atmospheric pressure) at a price from 3,000 €.

1. Introduction
Presently there are needs for cost-efficient, simple and reliable sources of Low-temperature plasma. However wide application of thermal & non-thermal plasma and also plasma-chemical technologies, with "pure" microwave plasma torches is prevented by their high cost.

To date, the most usage was made with three types of plasma sources \([1]\)

1) electric arc plasma sources – with AC or DC power supply,
2) high-frequency (HF),
3) ultra high frequency (UHF), microwave (MW) plasma torches.

Historically, in the first industrial plasma sources have been used the arc discharges of DC and industrial frequency AC, currently they are the most extensively studied and widely used in industry.

The use of inductively coupled plasma began with invention of high-power HF vacuum tubes generators (in the range from 60 kHz to 60 MHz) It does gave the possibility to isolate the discharge from the electrodes and the walls of the discharge chamber to obtain a pure electrodeless plasma that does not have thermal and electrical contact with the elements of the plasma torch.

Next step in plasma technology was using of the frequency bands 915 and 2450 MHz allowed for industrial applications. Powerful generators on magnetrons are now widely used as power sources for microwave plasma torches.

2. Design low cost microwave generators for plasma torches
The cost of microwave generators for industrial heating can be estimated as \(\sim 1.5 \pm 2\) € per watt power \([2]\). An impedance coupling structures could even double this figure. At the same time, the
price of a microwave module of household microwave oven may be less than 0.1 € per watt. That price includes: magnetron, complex housing, high voltage transformer, ventilation, locking and control system, etc.

Therefore, it is quite reasonable to use the main components and accessories of household microwave oven as a cheap source of microwave energy for plasma torches. Mass production and competition of leading manufacturers in the global market provide high reliability of their products at very low cost.

For implementation these advantages it was necessary to solve several problems:

2.1. **Really continuous mode of magnetron generation**

The power supply circuit of the magnetron of a conventional microwave oven consist of a high voltage transformer loaded with a half-wave rectifier with a voltage doubling. Therefore, the envelope of the microwave signal is a microwave energy pulse of length about 1 ms with a repetition period of 2 ms that is half of the supply voltage period is expended on the energy storage process in the capacitor. This mode is not suitable for powering the plasma devices operating at atmospheric pressure. During the pause (~1 ms), ions in the discharge region can to recombine and the discharge region is blown off the discharge from chamber by working gas stream.

We have developed and designed a special scheme for high-voltage magnetron supply from a three-phase AC network using three step-up transformers, operating in the "three quarter-bridge with doubling, in parallel" configuration [3]. This scheme provides a ripple level of about 15% without the use of any additional circuitry techniques and tools, and it is more than enough to maintain a continuous plasma discharge at atmospheric pressure.

2.2. **Ability to control the level of continuous power**

This problem we solved by a discrete change in the ratio of the parameters of capacitive storage devices in voltage doublers for each phase. In this way can be provided of several discrete levels (from 0.4 to 3 kW) of the continuous output power of a magnetron microwave generator can be provided.

This power supply has a switchable or adjustable current of the cathode heating prolong the service life of the magnetron. It is also possible to equip the power supply with devices for measuring of the filament and anode current of the magnetron. A source with four levels of working power, with smooth control of the filament current and direct measurement of the anode current is shown in (figure 1).

![Figure 1. High-voltage magnetron power supply with four levels of operating power.](image1)

![Figure 2. Magnetron OM 75P (Samsung) converted to water cooling.](image2)
2.3. Increase the effectiveness of the magnetrons cooling system

To operate at higher power levels, we developed a technology for modifying the serial microwave magnetrons used in domestic and industrial microwave ovens from air to water cooling. Was designed and made the water radiator in the form of a split monoblock made of aluminum alloy, which has a fairly good thermal contact with both magnets and a tight fit to the magnetron body due to the power clamping of the split structure (figure 2).

For example, magnetron OM 75P (Samsung) with a rated output power of 1 kW, equipped with a monoblock water cooler, can generate a power of more than 2.5 kW during extended continuous operation. Moreover, the heat load at each of the three transformers of the power supply has decreased to the value of about 70% from the regular mode.

3. Decrease of high cost of components microwave plasma torches

It is easy to see that the microwave plasmathrones offered in the world market is built according to the following scheme: power supply – magnetron head – microwave isolator with water load – reflected power meter – matching device – actual plasma torch – sliding short circuit (figure 3).

With all the obvious advantages of such a classic approach, one can not ignore the high cost of each component of the scheme individually and entire installation as a whole. Thus, the total cost of only three items from the above list, namely: the matching device, the directional coupler and the circulator with the load, produced of UIY Tecnology Co., Ltd, China, is about 8,000 €. The total cost of the SAIREM (France) microwave plasma system with a microwave generator of 3 kW, presented on (figure 3), is about 17,000 €.

3.1. Design of low cost of the waveguide system

Continuing our traditional principle of minimal budgetary development, we have simplified the design of the waveguide path as much as possible – even at the cost of a possible reduction in some of the technical characteristics of the microwave plasma torch. We left only the most necessary components from the classical scheme: power supply – magnetron head – waveguide system – plasma source – water load and simplified the design of the waveguide path as much as possible (figure 4).

As we see, the waveguide system in our case is an all-welded stainless steel construction based on a standard rectangular profile of 100*50*2 mm. At the end of the waveguide, a bend in the H-plane is made and a resonant water load is located here. A matching inductive diaphragm is located along the line of the break of the waveguide.
Although the terminal dummy load, located after the plasma torch instead of a short circuit, absorbs some of the useful power and reduces twice the electric field in the waveguide (worsening conditions for ignition of the discharge), it is needed to protect the magnetron from the reflected wave in the absence of a plasma discharge. In the classical configuration, these functions are performed by the circulator with its load and the matching device with the corresponding system for measuring the incident and reflected waves in the supply waveguide.

It was shown by subsequent experience that the lack of the above structure should be regarded as an almost inability to adjust the waveguide channel parameters. In particular, the choice of the optimal location of the plasma torch relative to a matching diaphragm turned out to be quite a challenge.

3.2. Efficiency of the microwave power injection. Adjustment device

We have corrected the design of the water load using a movable half-wave Teflon transformer to be able to adjust value of the reflection. If such transformer located in a node of the electric field of a standing wave (which is formed between the diaphragm and a short-circuit of the waveguide), it minimally affects the electric field in the load and its input resistance. When the transformer is displaced towards one or another antinode of the standing wave in the load, the complex input impedance of the load is rearranged, and the maximum of the standing component of the electromagnetic wave in the main waveguide is displaced too. The design of this trimmer is simple; it does not contain any movable electrical contacts or even no metal parts at all (figure 5).

As shown by the measurements, with such adjustment it is possible to ensure the efficiency of the microwave power injection directly into the plasma up to 90% and more.

![Figure 5. Resonant water load with a movable half-wave Teflon transformer (left). Magnetron head and waveguide system with upstream plasma torch and adjustable water load (right).](image)

3.3. Pipe fittings and cooling systems

Continuing our traditional principle of maximum use of the ready-made components, we currently supply our microwave plasma systems with plasma torches, built on the basis of standard threaded stainless steel and brass fittings for metal pipes. Availability of fittings, at an affordable price and the huge assortment allows quickly select the configuration of the burner for a specific task. (figure 6).

As the plasma temperature can reach several thousand degrees, water cooling of the support branch pipe or the entire adjacent section of the waveguide make possibilities for long duration technological processes. (figure 7)
3.4. The primary ignition of a microwave discharge.

We have found a method for initiating a discharge by introducing a pointed graphite rod with a copper coating into the discharge chamber along the axis of the plasmathrone. To do this, it is necessary to observe several design conditions associated with achieving a resonance along the length of the graphite rod. Automatic ignition mode can be provided with this method, if needed.

The limited volume of the article does not allow us to talk about our developments in the introduction of powders into the plasma, the sources of nonthermal plasma, the plasma torch with a remote dielectric wall, and others exciting possibilities given by our design low cost microwave generators and plasma torches.

4. Conclusions

All of the above has allowed us to develop and produce simple, reliable, inexpensive and highly effective microwave plasma torches for different purposes with the ability to implement continuous technological processes around the clock.

References

[1] Encyclopaedia of Low-Temperature Plasma. Entrance Volume, Book 2. Ed. by V. E. Fortov. (Moscow: MAIK Nauka/Interperiodika, 2000) [in Russian]

[2] Tikhonov V, Ivanov I, Kryukov A and Tikhonov 2015 J. Prikl. Fiz. 5 102-6

[3] Tikhonov V, Pugashkin D and Chetokin Ya 2011, RF Patent No. 2480890