Microwave complex for obtaining low-temperature plasma at atmospheric pressure

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Abstract. Over the past two decades, the scientific and technological community has made significant efforts to develop, maintain and use atmospheric non-thermal (ANT) plasma because of its numerous scientific and industrial applications. The hardware complex was designed and manufactured to produce low-temperature and ANT plasmas at atmospheric pressure. The base of the designed complex is powerful (up to 3 kW) and inexpensive magnetron microwave generator. The complex includes three types of applicators, splitter, cable assembly and water load. The splitter allows adjustable sampling of microwave power from the waveguide path to the payload by 50 Ohm coaxial cable in the range from 0 to 400 W.

1. Introduction
Today in promising areas of science, medicine, industry and agriculture, there is an urgent need for simple, reliable, inexpensive sources of low-temperature plasma. Low-temperature plasma, unlike the high-temperature, “hot” plasma, used in works on thermonuclear fusion, where the temperature measured in millions of degrees, is non-equilibrium. Temperatures of ions, neutrals and free electrons in this plasma may differ by several orders of magnitude. This is because most of the electrical energy is embedded in the electronic component, while plasma ions and neutral components remain at a relatively low temperature.

Traditional plasma generators, such as electric arc, high-frequency and microwave plasma torches produce plasma with operating temperatures from several thousand to tens of thousands of degrees. According to physicists classification, such plasma also refers to low-temperature plasma. This subdivision is due to the importance of high-temperature plasma in the problem of controlled thermonuclear fusion [1].

Over the past two decades, the scientific and technical community has made significant efforts to develop, maintain and use atmospheric non-thermal plasma (ANTP) in which ions and neutral components remain near room temperature [2]. This allows the use of such ANT plasma for low-temperature plasma chemistry and for the processing of heat-sensitive materials, including polymers and biological tissues. The unique properties of ANTP – a strong thermodynamic non-equilibrium nature, low gas temperature, the presence of chemically active radicals, high selectivity provide a huge potential for use the “cold” plasma sources in a wide range of applications.
The growth and importance of the ANTP technology and its application has spread to a large number of areas, such as environmental engineering, aerospace engineering, biomedicine, textiles, food and agricultural technologies, analytical chemistry and several others [3]. Unique capabilities and diverse applications of the ANTP technology are associated with its enormous potential for ensuring environmental friendliness and energy saving, technological flexibility and the ability to create new products and technologies.

The purpose of this work is to present the universal hardware complex, designed to generate both traditional low-temperature plasma and two types of ANTP in the R&D works on new materials and technologies, and also to intensify existing technological processes.

2. Technical description of the complex

In the basic configuration hardware complex included the microwave generator with HV power supply, the set of replaceable elements of the waveguide path, the water load, the 50 Ω cable assembly with N-connectors and one or several ANTP applicators (figure 1).

Figure 1. Schematic diagram of components and blocks of the hardware complex.

The core of the presented hardware complex is a low-budget the 2.45 GHz magnetron microwave oscillator with a high-voltage power unit built on the magnetrons, transformers and capacitors used in microwave ovens for domestic and industrial use [4]. The output power of the microwave generator can be changed discretely from 0.5 to 3 kW. If the maximum required microwave power level does not exceed 1.5 kW, an air-cooled magnetron such as LG-246 can be used. In the case of higher output power, liquid cooling of the magnetron is necessary.

The main elements of the waveguide system made of stainless steel from standard rectangular profile 100×50×2 mm, with WR-340 flanges size. The waveguide path could be loaded onto the final resonant water load. Between the output of the microwave generator and the load, the waveguide path elements from the next set can be placed.

2.1. The microwave plasmatron on the main type $H_{01}$ oscillations in the waveguide

Continuing our traditional principle of maximum use of the ready-made components, now we supply our microwave plasma systems with plasma torches, built on the basis of standard threaded stainless steel and brass fittings for metal pipes [5]. Availability of fittings, at an affordable price and the huge assortment allows quickly select the configuration of the plasma burner for specific tasks (figure 2). As the plasma temperature can be reach several thousand degrees, water cooling of the support tube or...
the entire waveguide section creates opportunities for the implementation of long-term technological processes (figure 3).

![Figure 2. Plasma jet on standard fittings.](image)

![Figure 3. Additional water cooling.](image)

2.2. E-field concentrator

The E-field concentrator can be made of a stepped design or with a smooth change in the waveguide cross section – to increase the electric field strength in the area where the microwave plasma torch is located (figure 4). The narrowing of the waveguide can be symmetrical or one-sided.

![Figure 4. E-field concentrator of a stepped design with narrow Ar plasma jet.](image)

2.3. An inductive-type splitter

An inductive-type splitter is a coupling loop located on a narrow wall of the waveguide. The design of the coupler allows to change the communication value by rotating the loop plane, which is loaded on the N-type coaxial connector. At the maximum coupling value, of about 14% of the microwave generator power branches off into the coaxial. So in the main waveguide the introduced reflections do not exceed 4%.

The splitter controls selection of the microwave power up to 400 W from the waveguide path through the cable to the remote payload without using any additional adjustment and matching devices. The payload (ANTP applicator) is connected to the splitter using the cable assembly which is a 50 $\Omega$ section of a flexible coaxial cable with N-type connectors at the ends. It is possible to combine in one node the coupler and the microwave plasma torch (figure 5).

![Figure 5. An inductive-type splitter combined with microwave plasma torch.](image)
3. ANTP applicator

One of kind of the ANTP applicator design is shown in figure 6. The plasma reactor vessel and air cooling radiator made of aluminium alloy. The protective body of the applicator is made of Teflon. N-type cable connector located on the applicator cover. There is also the supply pipe for working gas (argon) and two hose connectors forced air cooling system of the reactor.

The combustion region of the discharges at the ends of the applicator electrodes placed as close as possible to the tip of the reactor flange, which is allows to expand the temperature limits of the impact modes on treated objects. Discharge Initiation of the plasma is carried out using a piezo ignition system located in the handle of the applicator. The ignition button is located directly on the end of the handle. A typical form of a streamer microwave discharge in Argon is shown in figure 7.

Figure 6. ANTP applicator. Figure 7. Image of an Argon streamer discharge.

Figure 8. The general view of universal hardware complex for obtaining of low-temperature and ANT plasmas.
At the bottom of the ANTP applicator, jet temperature around of 100–150 °C and depends on microwave power level and argon flow rate. With the distance, the plasma temperature drops smooth and at a distance of about 10 cm approaches the ambient temperature.

4. Conclusions
Our universal hardware complex (figure 8) was designed for both laboratory and industrial applications. It generates low-temperature and non-thermal microwave plasma at atmospheric pressure.

We are continue to develop more advanced new elements for future needs. For example, the sources of dielectric barrier microwave discharge for ANTP in a coaxial and waveguide structure, the applicators for studying the interaction of microwave plasma with various liquids et al.

To expand the technical and technological capabilities, the hardware complex can be additionally equipped with a microwave circulator, a contactless waveguide short-circuiting plunger and strip directional couplers to measure the incident and reflected waves.

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