A new type of non-thermal atmospheric pressure plasma source

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Abstract. The unique applications of Non-Thermal Atmospheric pressure Plasmas (NTAP) are associated with its enormous potential for providing technological capabilities for new products and technologies. In such plasmas, most of the electrical energy is deposited in the electron component of the plasma, while plasma ions and neutral components remain at or near room temperature. This paper presents the NTAP source that combines the characteristics of a dielectric barrier discharge (DBD) by discharge configuration and a non-thermal plasma jet (NTPJ) by plasma jet formation.

1. Introduction
The unique properties allows using the NTAP “cold” plasma for low-temperature plasma chemistry and for treating heat-sensitive materials, including polymers and biological tissues [1, 2]. Typical examples of NTAP sources are: corona discharge, glow discharge, dielectric barrier discharge (DBD) and non-thermal plasma jet (NTPJ).

DBD is a sequence of fast-flowing micro-discharges in a gas with duration from several to tens of nanoseconds, when at least one of the electrodes is separated from the gas by a dielectric barrier made of glass, quartz, ceramic or polymeric materials. A distinctive feature of NTPJ sources is their ability to launch a thin jet of non-thermal plasma (based on discharge in argon or in helium) up to several centimeters in the external environment, where the electromagnetic field can be very low.

The purpose of this work is to present the new type of non-thermal atmospheric pressure plasma source which combines the characteristics of DBD by discharge configuration and NTPJ by plasma jet formation.

2. Design development
This device is a stretch of a rectangular waveguide, short-circuited at the end and diaphragmed at the beginning, operating on the basic type of oscillations H₀ [3]. The length of the segment is chosen close to the resonance condition. Precise adjustment of the resonance frequency is made by moving the dielectric (Teflon) transformer. The value of the inductive diaphragm’s lumen was determined by calculation and refined empirically (figure 1, left).

The discharge tube is placed across the waveguide in the first antinode of the standing wave from the short-circuited end of the waveguide in such a way that its axis is perpendicular to the electric field...
vector (DBD configuration). In this zone, the height of the waveguide is reduced (like a platypus) to increase the E-field strength (figure 1, right).

![Figure 1](image1.png)  
**Figure 1.** Schematic drawing of the computational model (left) and a prototype of the NTAP source with the Argon discharge in a ceramic tube (right).

As a source of microwave was used a low-budget the 2.45 GHz magnetron oscillator built on the magnetrons, transformers and capacitors which apply in microwave ovens for domestic and industrial destination [4].

3. Experimental results
Quartz, ceramics and glass were tested as the material of the discharge tube. External cooling of the discharge tube was carried out by blowing air in the cavity of the waveguide.

3.1. The microwave plasma torch
Dielectric tubes with diameter from 5 to 10 mm were used for the experiments. The starting initiation of the discharge was carried out by introducing a thin heat-resistant wire into the discharge tube’s cavity. The work was carried out at a flow rate of Argon from 10 to 20 l·m⁻¹. The discharge burns steadily and stably.

The type and shape of the Argon plasma jet at the outlet of the ceramic discharge tube are shown in figure 2. On the left – view in the direction of the X axis, right – in the direction of the Z axis (axes are shown on the left in figure 1).

![Figure 2](image2.png)  
**Figure 2.** Argon plasma jet at the outlet of the ceramic discharge tube.
There were attempts that made to work with Nitrogen. Initiation of the discharge in Nitrogen is difficult in comparison with Argon, the discharge is less stable and there is a rapid overheating of the discharge tubes up to their destruction.

3.2. Temperature measurement
The flame temperature was measured at the tip of the plasma jet using a thermocouple, as it is shown in Figure 3.

![Figure 3. Measuring the temperature of the Argon plasma jet using a thermocouple.](image)

Some results of the measurements are given in table 1. The wall thickness of ceramic discharge tubes was 0.5 mm, quartz tubes – 1 mm.

| Tube material | Tube outer diameter (mm) | Argon flow rate, (min⁻¹) | Temperature (°C) |
|---------------|--------------------------|--------------------------|-----------------|
| Ceramics      | 6                        | 10                       | 350–370         |
| Ceramics      | 8                        | 10                       | 450–470         |
| Ceramics      | 8                        | 20                       | 340–350         |
| Quartz        | 8                        | 10                       | 280–320         |

3.3. High-speed macro photography of fast processes in plasma discharge
To study the fast processes developing in the microwave discharge, a megapixel high-speed video camera Phantom Miro M110, serial number 17412, produced by Vision Research, was used.

Video shooting was carried out both along the axis of the discharge chamber (Y axis in Figure 1 on the left) and from the shorted end of the waveguide in the direction of the X axis. In the latter case, only quartz tubes were used because of their transparency, and the hole for shooting is clearly visible in Figure 3.
Figure 4 shows several frames consistently showing a continuously repeating process of microwave discharge’s birth in the place of the entrance of the Argon’s flux into the cavity of the waveguide. Argon’s flux moves from left to right.

![Figure 4](image)

**Figure 4.** A continuous process of initiation of the microwave discharge. Sample rate 66 000 fps, period 15.14 µs, exposure 10.0 µs, resolution 128×152, bits per pixel P10 (Packed 10 log).

The following figure 5 shows several individual moments in the discharge tube in the middle of the waveguide. The direction of Argon’s flux is also from left to right.

![Figure 5](image)

**Figure 5.** A few moments of the Argon discharge process in the discharge tube in the middle of the waveguide. Sample rate 23 000 fps, period 43.46 µs, exposure 8.0 µs, resolution 256×256, bits per pixel P10 (Packed 10 log).

For a more detailed consideration of the various and very rapidly developing processes in the investigated microwave discharge, Figure 6 shows the sequence of the following directly after each other frames of high-speed shooting. The direction of Argon’s flux is also from left to right.

![Figure 6](image)

To compare the time scales of the events, we note that the period of oscillation of the electromagnetic wave with a frequency of 2.45 GHz is about \(0.4\times10^{-9}\) s. When shooting video at a frame rate of 23 000, the shooting period is \(43.5\times10^{-8}\) s, and at a frequency of 66 000 fps shooting period is \(15\times10^{-6}\) s. Thus, for the period of time between two consecutive frames in figure 6, the electric component of the field in the discharge tube has time to change its polarity several thousand times.
In addition to the above macro images of the ultra-fast camera, figure 7 shows photos taken from the output end of the discharge tube (Y-axis in figure 1), using a conventional iPhone.

![Image of macro images](image1)

**Figure 6.** The sequence of the frames following one after the other. Sample rate 23 000 fps, period 43.46 µs, exposure 8.0 µs, resolution 256×256, bits per pixel P10 (Packed 10 log).

![Image of iPhone photos](image2)

**Figure 7.** Some iPhone’s photos taken from the output end of the discharge tube.

![Image of orange jet](image3)

**Figure 8.** The «orange jet» at the glass discharge tube's outlet.

![Image of testing non-thermal properties](image4)

**Figure 9.** The moment of testing the non-thermal properties of the «orange jet».
3.4. **Observation of the "orange jet" effect**

An interesting effect was found when using a discharge tube made of ordinary laboratory glass. About a minute after the discharge is initiated in the Argon flow, a glowing orange jet appears at the outlet of the glass discharge tube (figure 8).

The temperature measured using a thermocouple at the tip of the "orange jet" was about 180–200 °C, that is significantly lower than the values given in table 1 for ceramics and quartz (figure 9).

4. **Conclusions**

Thus, the first study's results of the properties of microwave discharge, which combining the inherent properties of DBD and NTPJ was presented. The images taken by the high-speed video camera revealed an extremely interesting and diverse nature of the processes occurring in such a discharge. The authors consider it obvious that further, more rigorous and in-depth studies of the phenomenon described above are needed.

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