

PSFC/JA-02-2

**Large Electroless Plasmas at Atmospheric
Pressure Sustained by a Microwave
Waveguide**

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January 2002

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To be published in IEEE Transactions on Plasma Science

**Large Electroless Plasmas at Atmospheric Pressure
Sustained by a Microwave Waveguide**

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Abstract- A 1.5 kW, 2.45 GHz magnetron source has been used to reliably sustain large electroless plasmas at atmospheric pressure in a shorted waveguide without a resonator. Working gases have been air, nitrogen, and heated off gases of sulfur containing ores and coal in nitrogen. Various colorful plasmas of value to environmental monitoring and processing applications are generated depending on the composition of the working gas.

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Large electrodeless plasmas can be efficiently sustained by microwaves at atmospheric pressure in a variety of gases without the need for a high Q resonator. Such plasmas are of value for environmental monitoring and processing applications. Advantages include clean and wear resistant electrodeless operation, high throughput atmospheric pressure, 100% efficient microwave to plasma coupling, and availability of inexpensive sources at 2.45 and 0.915 GHz.

A recent test of the microwave plasma torch, shown here, for real-time stack off-gas metals emission monitoring has demonstrated high sensitivity ($< 3 \mu\text{g}/\text{m}^3$) and accuracy for beryllium, lead, and chromium [1]. Sensitive mercury and arsenic detection in air is under development [2,3]. Studies of the microwave plasma temperature in air and nitrogen have shown molecular rotational and electronic excitation temperatures in the range of 5000 to 6000 K [3,4] and studies of temperature profiles suggest electron densities of order 10^{13} cm^{-3} [5].

The capability to operate at high temperatures and pressures in non-oxidizing environments makes the microwave plasma torch a useful tool for research into environmentally clean processing alternatives for refining ores and cleaning fossil fuels, which are major sources of sulfur dioxide and mercury pollution. Brilliant and colorful plasma flames are generated in the course of such experimentation, which can be quantitatively studied by optical and UV spectroscopy [1-5].

Figure 1 shows four atmospheric pressure microwave plasma flames photographed with a digital camera. Microwave drive power is 1.5 kW at 2.45 GHz, with zero reflected power and total gas flow rate of 22 lpm. Left to right the plasma gases are

a) air, b) nitrogen, c) nitrogen with about 2% (mass fraction) sulfur from a heated copper ore (chalcopyrite), and d) nitrogen with sulfur and unidentified hydrocarbon off gases from coal heated to 500 °C.

The underlying structure that sustains and confines the plasmas in Figure 1, and not clearly visible, is outlined in Figure 2. A standard WR-284 waveguide tapered to a shorted cross-section of 72 x 17 mm directs the power to the discharge. A 32 x 13 mm opening in the short covered with a 12 wires per mm (300 wpi) Buckbee-Mears electroformed copper mesh allows a view of the bright microwave driven part of the plasma in the lower part of the Figure 1.

A 305 mm long fused quartz tube passes vertically through the wide walls of the waveguide to confine the plasma gas flow. This tube has internal and external diameters of 28 x 32 mm. It is located one-quarter wavelength (30.6 mm) from the short to facilitate plasma startup. The hot plasma is further confined by tangential gas jets near the bottom of the quartz tube, which inject a swirl gas flow to keep the plasma off the quartz walls. The swirl gas is either air (a) or nitrogen (b), (c), (d) and accounts for about 25% of the total gas flow through the waveguide.

The color of the plasma flame is determined by the atomic and molecular species that are excited to emit light. In the pure nitrogen plasma (b) the dominant light emission species are the vibrational bands of N_2 and N_2^+ with the violet N_2^+ first negative system, $B^2\Sigma_u^+ - X^2\Sigma_g^+$, 0-0 band dominate in the waveguide driven region. In air (a) the N_2^+ bands are suppressed, but prominent NO and OH vibrational bands in the ultraviolet along with a broadband continuum produce the whitish light blue flame.

When chalcopyrite was processed above 400 °C in nitrogen, the 2% elemental sulfur added to the nitrogen flow caused a long deep blue afterglow (c). The transition(s) responsible for the blue color have not yet been identified, but strong UV emission on the sulfur ground state transitions at 182.62, 182.03, and 180.73 nm are prominent in the waveguide driven region when viewed with a spectrometer flushed with nitrogen to allow propagation of these wavelengths. Hot processing of sulfur containing coal in (d) produced sulfur emission, but at slightly higher temperatures (>400 °C) another off gas component causes intense broadband emission to produce a bright crimson-white flame. Future spectroscopic studies of this light may provide insights into new environmentally clean refining and energy technologies.

ACKNOWLEDGMENT

The authors gratefully acknowledge Kavetech and Stanley Yake for support of the mineral and coal experiments, and Miklos Prokolab for encouraging publication of these images.

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FIGURE CAPTIONS

1. Atmospheric pressure, 1.5 kW, 2.45 GHz microwave discharges in a) air, b) nitrogen, c) nitrogen with 2% sulfur, d) nitrogen with the off gases from coal heated to 500 °C. Gas is blown in from bottom to top. The lower bright region is a view into the end of the waveguide where the microwaves drive the plasma. The photos were taken with an Olympus Model D-600L, 1.4 mega pixel camera set for maximum exposure reduction.
2. Sketch of the device sustaining and confining the plasma in Figure 1.

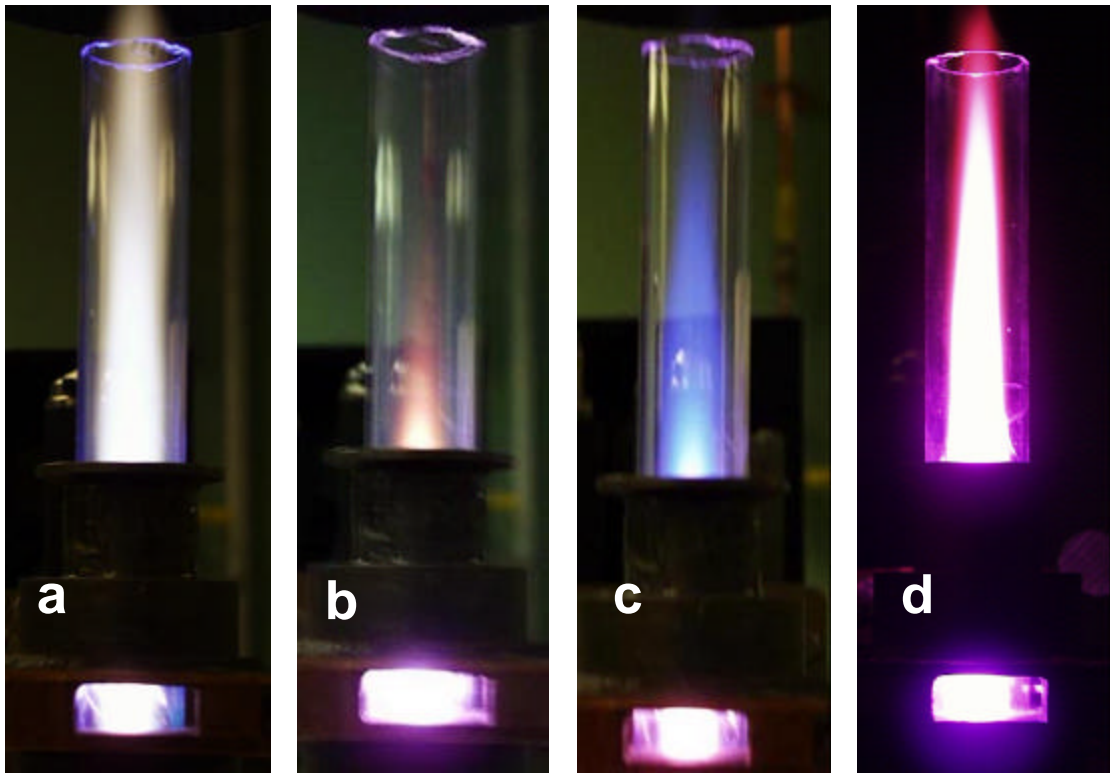


Figure 1.

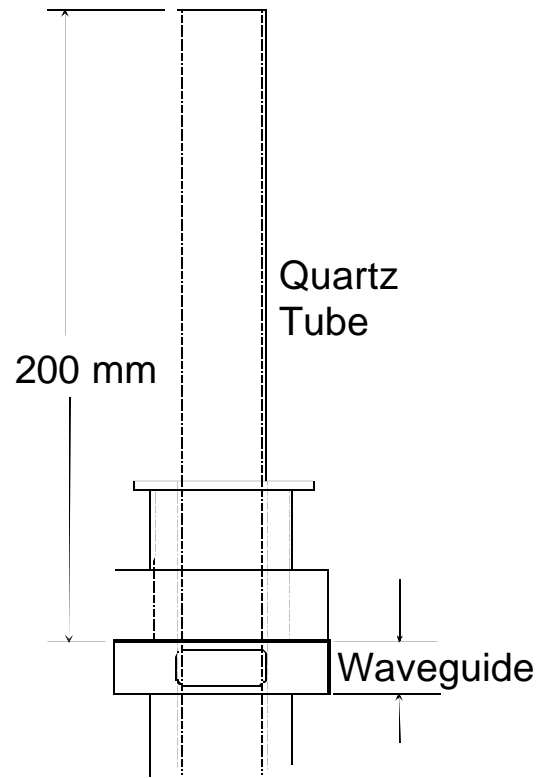


Figure 2.