Microwave discharges: generation and diagnostics

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Abstract. Microwave discharges are widely used for generation of quasi-equilibrium and nonequilibrium plasma for different applications. Microwave plasma can be generated at pressures from $10^{-5}$ Torr up to atmospheric pressure in the pulse and continuum wave regimes at incident powers ranged between several Watts and hundreds of kW. The plasma absorbed power can be high enough and runs up to 90% of the incident power. This paper reviews the methods of microwave plasma generation, general features of microwave plasma, and selected aspects of microwave plasma diagnostics.

1. Introduction
Microwave discharges (MD) are the electrical discharges generated by the electromagnetic waves with frequencies exceeding 300 MHz (wave length $\lambda_{[cm]}=30/f_{[GHz]}$). The used wavelengths of microwaves are in the range from millimeters up to several tens of centimeters and should correspond to permitted microwave frequencies for industrial, medical and scientific applications. The frequency 2.45 GHz is the most commonly used.

The starting stage in development of MD and microwave induced plasma (MIP) was strongly coupled with successes in radar technique. For example the antenna switches are the microwave gas discharge plasma devices which use the high power microwave pulse for plasma generation to prevent the damage of low signal microwave receiver in the moment of passing this pulse through the microwave circuit. Further development of microwave technique created the necessary prerequisites for application microwave devices in different areas of science and technique and in particular for generation of gas discharge plasma. Now MDs are widely used for generation of quasi-equilibrium and nonequilibrium plasma for different applications: for generation of the active medium in the gas discharge lasers, light sources, in plasma chemistry, analytical chemistry, for creation of artificial ionized areas in the Earth’s atmosphere, recovering of the Earth’s ozone layer, etc. MD is the nonelectrode discharge and has some advantages over other types of electrical discharges [1-14]:
- the simplicity of plasma generation both with high ($>100W/cm^3$) and low ($<1W/cm^3$) levels of absorbed powers;
- the wide region of operating pressures (from $10^{-5}$ Torr up to atmospheric pressure);
- the simplicity of control the plasma internal structure by means of changes in electrodynamic characteristics of microwave-to-plasma applicator;
- the possibility of plasma generation both in small and large chambers, including the free space;
- the possibility of plasma generation in the electrode discharge systems without any contamination of gas phase or plasma treated samples by products of the electrode erosion;
• the possibility to treat a large gas volumes (including a cleaning process for the reactor walls) by scanning the plasma region (which is small as compared with chamber dimensions) over the chamber;
• the possibility to realize of joint action of the plasma and electromagnetic field on the treated substances (e.g., powders) to increase the energy efficiency of plasma chemical process;
• the developed family of the highly effective microwave-to-plasma applicators permits to choose the necessary design for any application.

MD can be generated in the pulse and continuum wave regimes at incident microwave powers ranged between several Watts and hundreds of kW. The plasma absorbed power can be high enough and runs up to 90% of the incident power. Plasma density usually exceeds the critical density \( n_{ec} \approx 1.24 \times 10^{10} f^2 \text{ [GHz]} \). Problems of comparison of MIP properties and plasma of other discharges are analyzed in ([10] Pr7-369).

Information of MD is presented in numerous books, journal papers and in the Proceedings of many plasma conferences. Two of conferences should be specially mentioned because they contain the comprehensive information on MD. It is the International Workshop “Strong Microwaves in Plasmas” (“Strong Microwaves: Sources and Applications” since 2008) [6, 7]. The second one is the International Workshop “Microwave Discharges: Fundamentals and Applications” [8-14]. This review is mainly based on these Proceedings and it permits to shorten the list of references.

2. Microwave plasma generators

2.1. Typical structure of microwave plasma stand (microwave plasma generator)

The microwave plasma generators typically include several elements (figure 1). It consists of the microwave power source (usually the magnetron generator), element protecting the magnetron from the reflected power (any nonreciprocal device, e.g., circulator), standing wave ratio meter, matching circuit and microwave-to-plasma applicator. The last one is the main element of plasma generator because it realizes the input of microwave energy to plasma. It defines the efficiency of plasma generator (the portion of the incident power absorbed in plasma), levels of minimal and maximal plasma powers, bandwidth of the system, and structure of electromagnetic field in plasma, uniformity and size of plasma. Depending on the properties of the applicator some of elements can be removed from typical structure of microwave generator (figure 1). For example it can realize the matching functions and in that case the microwave generator can be directly connected with the applicator. The applicator defines also the correlation of external (pressure, power, frequency, etc) and internal (mean energy and energy distributions of plasma particles, electron density, etc) plasma parameters. Therefore the term “MIP” unites the plasma objects with different structures and internal parameters and the field frequency is the only common quantity. It is not enough for plasma characterization especially for comparison with the plasma of other types of discharges. So the most correct approach is considering the MIP in the particular applicator (it is the MD).

![Figure 1. Typical structure of the microwave plasma stand](image-url)
Engineering methods used in designing the microwave-to-plasma applicators are defined by requirements to microwave devices and elements with electrically distributed parameters (waveguides, resonators, etc). All existing applicators can be conditionally divided into several classes:

- cavity microwave plasma generators;
- waveguide microwave plasma generators;
- surface wave plasma generators;
- slow wave plasma generators;
- wave beam microwave plasma generators;
- microwave plasma generators with distributed energy input;
- initiated microwave discharges;
- electrode microwave plasma generators;
- microwave plasma generators with external magnetic fields;
- plasma generators with combinations of microwave and other fields.

It is non-unique principle of applicators classification. For example, almost all low pressure microwave plasma generators on the base of physics of microwave power absorption can be classified as the generators with “plasma resonance”.

Several examples from numerous microwave plasma devices will be presented below.

2.2. Cavity microwave plasma generators (figure 2)

First two classes of plasma generators (#2.2, 2.3) can be referred to so-called plasma generators with the “localized discharge zone” as the discharge exists inside the applicator and the discharge sizes are limited by it dimension (characteristic dimensions of plasma are less than the wavelength).

Cavity plasma generators are among the first microwave plasma generators. Plasma exists in the low losses dielectric tubes (quartz, ceramics) placed in the prismatic (a, e), coaxial (b), cylindrical (c, d, g), opened (f) resonators. High and low quality resonators are used for generation of plasma with density exceeded \( n_c \) but the density less than \( n_c \) can be obtained in the high quality resonator.
2.3. Waveguide microwave plasma generators (figure 3)
Electromagnetic energy is introduced in plasma in the discharge tubes by rectangular, cylindrical or coaxial waveguides. Discharge tubes orientation respectively to the waveguide axis can be different. Plasmatron on the mode H\textsubscript{10} (a) is one of the simplest and widespread plasma generator from this class. To improve the matching of the applicator the length of one part of the parted waveguide can be increased by \( \lambda/4 \) respectively to another part (b) or the discharge tube can be placed at a certain angle to the waveguide axis (c). Long slab of plasma can be generated in the tubes placed along the waveguide axis. To increase the uniformity of plasma slab the waveguide dimensions can be changed along the tube (c) or one can feed the applicator from the opposite ending of the waveguide.

2.4. Surface wave microwave plasma generators (figure 4)
Special classes of microwave applicators were designed to increase the plasma sizes. In contrast to first two classes they are based on the “propagating waves” or ‘radiating structures’. It the first case plasma exists outside the applicator and sustained by the surface waves (SW).

These types of applicators have large bandwidth, can generate microwave plasma inside the dielectric tube (figure 4, a, b, c, d), in free space (e) and outside the tube (f).

Figure 4. Different designs of surface wave devices on the base of cylindrical (a, d) rectangular (b, c) and coaxial structures (e), duo-plasmaline ([10] Pr7-99) (f), large area surface wave plasma source (g) ([11] p. 163)

2.5. Microwave plasma generators with radiating structure: slow wave plasma generators, wave beam microwave plasma generators
Slow wave systems are the periodic structures served for reducing the phase velocity of electromagnetic wave. Electromagnetic field existing near such structures can be used for large volume plasma generation. As the field structure is non-uniform, special methods should be applied to increase the plasma uniformity. For example it is possible to use two similar slow wave structure having inputs from opposite ends.

Unique possibilities of microwaves for plasma generation give the wave beams. Plasma can be generated in the region of maximal electric field in the focused wave beam. Crossed beams can be
used to stabilize the plasma position. This is the source of freely localized discharge which can be initiated in the Earth’s atmosphere.

2.6. Microwave plasma generators with distributed energy input (figure 5)

Generators of this class can produce the large area/volume plasma and give possibility to change the internal plasma spatial structure. The powered waveguide is connected with the discharge chamber by adjusted couplers (rods, slots, orifices) to control the necessary level of plasma uniformity.

![Figure 5](image)

**Figure 5.** (a) Waveguide holey-plate plasma generator ([11] p.175) and (b) SLAN-system (slotted antennas) ([10] Pr7-1)

2.7. Initiated microwave discharges, electrode microwave plasma generators (figure 6)

Initiated microwave discharges are the discharges which exist at low levels of incident microwave power and can not be ignited without any initiator (ionizing radiation, auxiliary electrode, solid particles, etc). Their peculiarities are:

- low maintaining power;
- localization of the plasma region;
- large volume/area plasma can be produced by the specially adjusted set of initiators;
- possibility of the electric field strength control in a plasma;
- strongly nonequilibrium plasma at atmospheric pressure.

![Figure 6](image)

**Figure 6.** Resonance antenna initiator (a) [15] and electrode microwave discharge (b) [16]

2.8. Microwave plasma generators with external magnetic fields (figure 7)

Any microwave plasma system can be placed in the magnetic field to provide:

- the transport of plasma particles to the necessary direction (a);
- the matching of plasma device with the microwave power transmitted line;
• the limitation of plasma zone (protection of the walls, dielectric windows from the action of plasma, decrease of the charged particles losses which leads to decrease of microwave maintenance field strength, etc) (b, c);
• the ECR-regime (f(\text{Hz})=f_{ce}=2.8 \cdot 10^{10}B_0(T)) (d);
• the plasma anisotropy.

**Figure 7.** Microwave plasma generators with external magnetic fields  
**Figure 8.** Plasma generator with combination of MW and RF fields.

2.9. Plasma generators with combinations of microwave and other fields (figure8)  
Combined discharges are used if it is necessary to:
• use the positive properties of each of discharges;
• generate the plasma at power levels insufficient for existence of self-sustained discharge;
• produce plasma with desirable properties (additional possibility of control the plasma parameters; widening of range of variation of parameters; increase the active particle densities, homogeneity, etc);
• increase the stability of plasma system.

3. Diagnostics of microwave discharges
All methods of plasma diagnostics which are successfully used in other types of discharges can be applied for diagnostics of microwave discharges taking into consideration the peculiarities of microwave plasma. Besides that it is necessary to mention that almost all modern methods of diagnostics are the experimental-computational methods and require either, one or another plasma model to process the experimental data for calculation the plasma parameters. These models should also correspond to the plasma peculiarities.

First of all when choose and apply methods of diagnostics it is necessary to take into account the inherent non-uniformity of microwave plasma (if special methods do not used to suppress it) and level of non-uniformity is often unknown a priory. Reasons of this non-uniformity are:
• skin-effect produces non-uniform microwave field;
• plasma resonance can produce the non-uniform and non-Ohmic power absorption;
• regions of plasma resonance can generate the electron beams and produce the anisotropy of plasma (this effect was observed at pressures below 50 mTorr);
• electrons in non-uniform microwave filed experience a force proportional to $\nabla E_m^2$. These force can causes the spatial redistribution of electrons in plasma. Within the range of fields strength used in low power low temperature plasma devices (e.g., in plasma chemistry) the electron spatial distribution is not disturbed by non-uniformity of microwave field.

Level of non-uniformity of microwave plasma depends on the power consumption, pressure, plasma gas, electric field frequency, discharge chamber design (e.g., the shape of electrodes, or microwave-to-plasma applicator, etc.). Thus the integral methods of plasma diagnostics give serious error not only in the averaged plasma parameters but also in the dependences of parameters on plasma conditions. This means that the methods of diagnostics with spatial resolution should be used in general for diagnostics of microwave plasma.

Another source of measuring error is related with direct influence of microwaves on measuring device (e.g., electrostatic probe, thermocouple).

Several methods of microwave plasma diagnostics will be considered below. The fundamentals of the methods are described in numerous books (see e.g. [17-19]). Here we emphasize the difficulties and possibilities of methods in measurements of the key microwave plasma parameters.

3.1. Electrodynamic measurements

Electrodynamic measurements give information both on microwave-to-plasma applicator with plasma (MD) and MIP, e.g. it is possible to define the plasma impedance and then calculate the averaged plasma parameters (electron density and temperature). Technique and approaches are similar to that used in microwave plasma diagnostics (see e.g. [20]). Here we consider measurements of one of the most important plasma characteristics, namely the plasma absorbed power $P_{\text{abs}}$. This parameter is used in plasma physics and applications.

If the plasma is the only source of microwave power losses in the system, $P_{\text{abs}}$ can be defined from the power balance equation using the measured incident $P_{\text{in}}$ and reflected $P_{\text{ref}}$ powers:

$$P_{\text{abs}} = P_{\text{in}} - P_{\text{ref}}.$$

The real situation is more complicated and there are additional sources of microwave power losses:

• losses in the walls of the discharge chamber and transmitted lines and connectors (these losses grow with increasing standing wave ratio);

• radiation from the windows and leakage from different microwave connectors.

It is difficult to separate these sources of losses from the absorption of microwaves by plasma.

It is also necessary to take into account the sources of errors in the power measurements:

• Error in the measured incident power in the case of high standing wave ratio in the point of measurement (the mode of pure running wave should be realized).

• Error in the measured powers can be caused by the fact that the powered microwaves can contain not one frequency only but the set of frequencies of comparable amplitudes and their correlation depends on microwave power and matching of the plasma load. This source of error is important if the resonant measuring systems are used in the power or the standing wave ratio meters.

These factors complicate the measurements of plasma absorbed power and cause the uncontrollable error in the measured $P_{\text{abs}}$. To get over the difficulties it is possible to use several methods.

The direct measurement of the plasma absorbed power by calorimeter is one of the methods. Energy deposited in plasma is lost through the walls of plasma chamber and/or carried away with the gas flow. In the case of low flow rate or in low pressure plasma the first channel is the main and to measure $P_{\text{abs}}$ it is necessary to calorirometry the walls of discharge tube (figure 9). The calorimeter liquid should be low-loss dielectric at microwave frequencies because it operates under the action of electromagnetic field. Organic silicon oil or liquids can be used for this purpose. In the case then the gas flow is the main channel of energy losses, the calorirometry of gas flow can be done outside of the applicator where the electromagnetic field is absent and requirements to the dielectric is softer.

If the electromagnetic field in the applicator is slightly disturbed by the presence of plasma, $P_{\text{abs}}$ can be defined by subtraction of power absorbed in the system without plasma (blank measurement) from...
the power absorbed in the system with plasma. Results are shown in figure 10. It is seen that the corrected power curve differs markedly from uncorrected curve.

Figure 9. Calorimetric method of measurement of plasma absorbed power.[21] Figure 10. Measurement of plasma absorbed power by subtraction of blank absorption.[22]

3.2. Probe measurements in microwave plasma.
Electrostatic probes are the effective tool for local diagnostic of parameters of charged components of plasma [23-27]. The same as any invasive methods the probes can cause the perturbation of plasma. In microwave (and RF) plasma diagnostics there are additional disadvantages: perturbation of electromagnetic field, perturbation of probe voltage-current characteristic (VCC) by electromagnetic fields. Here we will consider the role of the last factor [26].

Figure 11. Influence of alternating field on VCC (a) and its second-order derivation (b) (theory).
Figure 12. Influence of alternating field on VCC (a) and its second derivation (b) (experiment).

Nature of VCC perturbation by electromagnetic fields is related with nonlinear voltage-current probe (probe sheath) characteristics and frequency transformation of alternating signal $v_0$ applied to the sheath. Rectification of alternating sheath voltage leads to appearance of DC voltage in addition to the external DC probe voltage (so-called “self-biasing of the probe”) which moves VCC along the
voltage axis. Since the nonlinearity of VCC depends on the external DC voltage (the operating point), the self-biasing is also the function of it. This effect leads not only to parallel move of VCC along the axis but also to deformation of it. This deformation in one’s turn causes the deformation of the voltage second-order derivation of VCC which defines the electron energy distribution function. Methods of minimization of this error are clear from equivalent probe circuits (figure 13).

Figure 13. DC (a) and rf (b) equivalent probe circuits: U is the probe voltage; Rmes is the measuring resistance; Rp, Rrp, Rpl and Zp, Zrp, Zpl are the resistances and impedances of the probe, reference probe and plasma, resp.; Ep and Erp are the emf of the probe and reference probe sheaths; Cs is the stray capacitance; F is the high-impedance filter; b and c are the positions of probe and reference probe in plasma; \( \Delta U_{pl} \) is the difference in the space potentials in the places of probe and reference probe; \( \Delta U_{fl} = \Delta U_{pl} + u_0 \sin(\omega t) \).

To decrease the influence of microwaves on the probe results it is desirable to:
- place the probe and reference probe on the equipotential surface for the alternating field. This approach is generally realized in the double probe method;
- increase the probe surface (decrease both the probe impedance \( Z_p \) and the internal alternating signal \( u_\sim \) applied to the probe sheath when other circuit components being equal). It is necessary to take into account the increase of negative influence of geometric plasma perturbation and electron depletion in the vicinity of the probe due to increased probe current;
- increase the impedance of the external part of the probe circuit (application of high-impedance resonant filters, e.g. cavities (“F” in figure 13b)). Good results for the double probe method give introducing of resistors (20-30 kOhm) in series with the probes. Filters should be placed at the minimal distance from the collecting surface of the probes to suppress the role of the stray capacitors \( C_s \);
- use the external alternating signal of necessary frequency, amplitude and phase in the probe circuit to compensate the alternating signal from plasma (active method).

Application of all above mentioned methods can minimize the influence of microwave field on VCC. Absolute criteria of residual influence of microwaves are absent. To prove the real probe accuracy it is necessary attract the additional information. Minimal VCC distortion can be indicated by minimal probe floating potential which depends on \( u_0 \)

\[
\Delta U_{fl} = -\frac{kT_e}{e} \ln I_0 \left( \frac{eu_0}{kT_e} \right)
\]

Correct use of probe method give information on the density and mean energy of electrons, electron energy distribution function. Use of the probe technique together with the Boltzmann equation gives information of the electric field strength in plasma (see e.g. [28]).

3.3. Measurement of plasma emission integrated over spectrum.
Spatially resolved plasma emission integrated over spectrum gives information on the structure of MIP. Since the plasma emission is proportional to the specific absorbed power these measurements show the distribution of the power consumption over the plasma volume (e.g. [29]).
3.4. Optical emission spectroscopy

Method of optical emission spectroscopy is described in detail in numerous monographs (e.g. [17-19]).

3.4.1. Measurements of gas temperature.

The gas temperature $T_g$ is an important parameter that determines both the interaction of the electromagnetic field with the plasma (via the ratio $\nu/\omega$, where $\nu$ is the effective collision frequency of electrons with heavy particles) and kinetics of the plasma processes. Here we will consider two methods which are widely used in studying plasmas with spectral devices having a low and moderate spectral resolution. Measurements with spatial resolution give information on gas heating process.

The gas temperature in nitrogen plasma can be determined from the unresolved rotational structure of the molecular rotational–vibrational–electronic transitions, assuming that the rotational and gas temperatures $T_{\text{rot}}$ and $T_g$, are equal to one another [30-37]. The temperature $T_{\text{rot}}$ is determined by comparing the measured and calculated spectra of the second positive system of nitrogen (figure 14).

For the measured rotational temperature $T_{\text{rot}}$ to be equal to the actual gas temperature $T_g$, it is necessary that the following conditions are satisfied: the populations of the rotational levels of an electronically excited state should obey a Boltzmann distribution; in the electronic state from which the excitation occurs, there should be equilibrium between the rotational and translational degrees of freedom; the mechanism for a change in the rotational distribution after excitation should be known; the kinetic processes responsible for the population of the excited state under study should not disturb the rotational distribution; the rotational relaxation time should be shorter than the residence time of molecules in the discharge; the lifetime of the electronically excited state under analysis should be much longer than the rotational relaxation time; and the emission in the bands under study should not be reabsorbed.

![Figure 14](image)

**Figure 14.** Calculated (curves 1–3) and measured (circles) emission spectra of the second positive system of molecular nitrogen in the spectral range 325–360 nm from electrode microwave discharge in nitrogen at a pressure of $p = 1$ Torr; gas flow rate of 20 sccm; $P_{\text{in}} = 70$ W; and $T_{\text{rot}} = (1) 900$, (2) 700, and (3) 550 K. The inset shows $T_{\text{rot}}$ as a function of $P_{\text{in}}$.[37]

The gas temperature in hydrogen plasma can be determined from the relative intensities of rotational lines of the electron excited molecules H$_2$(d^3Π_u) (bands of Fulcher $\alpha$-system H$_2$(d^3Π_u→a^3Σ_g$) [38, 39]. Rotational temperature of the ground state of H$_2$ is calculated taking into account the ratio of rotational constants of the ground ($B_0$) and excited states ($B'$) ($T_{\text{rot0}} = T_{\text{rot}} B_0/B'$). This method can be used only if the H$_2$(d^3Π_u) state is depopulated via a radiative transition to the ground state and the collisions with atoms and molecules can be neglected.
3.5. Measurements of electron density and electric field strength

Method of relative intensities of lines or bands emission in combination with measurements of absolute intensities of emission (absolute populations of radiating states) is used for non-invasive measurements of electron density and electric field strength measurements [40-45]. As usual the assumption that the electronic states are excited by electron impact and quenched via radiative decay without reabsorption (coronal model) applied for processing of experimental data. The correctness of the coronal model should be proved for conditions of each experiment. It is the simplest case of application of the method but more complicated models of excitation of plasma emission can be used if necessary for realization of this method.

For example the method applied to microwave nitrogen discharge included several successive steps [44]. The experimental ratios of $2^+$ and $1^-$ nitrogen plasma intensities were modeled on the base of kinetic model which includes the calculation of the electron energy distribution function. Electron densities $n_e$ were defined from the absolute intensities of nitrogen bands emission. This iteration procedure was continued up to full agreement of experimental and calculation results giving the values of electric field $E$ and $n_e$.

In hydrogen microwave plasma small quantity of Ar was added for diagnostics and intensities of $H_α$, $H_β$ and Ar lines were measured [45]. If Ar lines are excited by electron impact and $H_α$, $H_β$ lines are excited by electron impact in the processes of dissociative excitation of $H_2$, processing of ratios of $H_α$/Ar $H_β$/Ar intensities and absolute values of lines give the values of $E$ and $n_e$. This method contains the internal criteria of correctness of the procedure: the values of $E$ and $n_e$ calculated using the lines $H_α$ and $H_β$ should be equal.

4. Summary

- Microwave plasma generators can produce the quasi-equilibrium or non-equilibrium plasma in wide region of pressures, powers in different gases providing manifold internal plasma parameters.
- Any plasma process can be realized on the base of devices from the already designed family of different effective microwave-to-plasma applicators. New microwave plasma devices are continually developed. Efficiency of microwave plasma application in comparison with other discharges should be analyzed in each case.
- Diagnostics of microwave plasma is complicated by presence of microwave field and non-uniformity of plasma.
- These facts should be taken into account in the realization of discharge diagnostics and modeling. Spatially resolved diagnostic methods should be used for microwave plasma diagnostics.
- Competent use of probe and optical methods for microwave plasma diagnostics gives information on gas temperature, spatial distributions of plasma absorbed power, microwave field strength, electron density, and densities of plasma particles.

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