University of Tennessee

Plasma Sciences Laboratory

Paper 5P-29

TIME-AVERAGED ELECTRON NUMBER DENSITY MEASUREMENT OF A ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA (OAUGDP™) BY INTERACTIONS WITH MICROWAVE RADIATION*

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Presented at the 29th IEEE International Conference on Plasma Science
Banff, Alberta, Canada, May 26-30, 2002

* **Supported in part by AFOSR Contract AF F49620-01-1-0425, Dr. John Schmisseur, Program Manager**

ABSTRACT

A simple and accurate technique for measuring the time-averaged electron number density and the electron collision frequency of a glow discharge at atmospheric pressure is described. It is based on the plasma-induced absorption and propagation delay of an incident microwave signal. The method is applied to estimate the time-averaged electron number density of a layer of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) [1] generated in air on a dielectric-covered reflective substrate on which a series of parallel, plasma-generating electrodes are located [2]. In the case of microwave propagation through this plasma, the refractive index is complex, and the propagating wave is delayed relative to vacuum propagation, and drops off exponentially from the boundary of incidence. The flux density drops by a factor of e^{-1} after the wave has propagated a distance δ, known as the skin depth. The skin depth is inversely proportional to the square root of the electron number density [1].

Reference [2] describes a steady-state, uniform glow discharge plasma at one atmosphere pressure that can be generated in a thin surface layer air and other gases. This OAUGDP™ layer is generated by applying an RF signal of 1-20 kHz on a dielectric flat panel covered with parallel strip electrodes. The electron number density of the plasma layer is periodic with the applied RF signal. If microwave radiation propagates through the plasma layer, the attenuation is proportional to the round-trip path length of the reflected wave. A 20 dB horn antenna, operating at 12 to 18 GHz, was used both at the transmitter and the receiver end. We compared the change in the propagation time and the intensity of the reflected signal with the plasma layer on and off. At normal incidence, our experimental results should be given by a relatively straightforward numerical calculation based on Appleton's equation [1]. In the plasma layer, the thickness of which is 0.3mm, we were not able to measure the time delay of the radiation, but were able to estimate an upper and a lower bound for the average electron number density from the attenuation measurements.

[1.] J. R. Roth (1995): *Industrial Plasma Engineering*, *Volume 1 – Principles*, Institute of Physics Press, Bristol, UK ISBN 0-7503-0318-2, Section 12.5.2.

[2.] J. R. Roth, "*Method and Apparatus for Covering Bodies with A Uniform Glow discharge Plasma and Applications Thereof*". U. S. Patent #5,669,583, Issued Sept 23, 1997.

INTRODUCTION

- At one atmosphere of pressure, the electron collision frequency is terahertz, far above the tens of gigahertz normally used for microwave interferometry. This makes the phase angle a function of the electron collision frequency, and rules out conventional microwave interferometry as a diagnostic tool for electron number density measurement.

- A glow discharge at atmospheric pressure has an electron mean free path that is less than one micron. This is well below the Debye shielding distance, seriously compromising the use of conventional Langmuir probe theory to obtain the electron number density and kinetic temperature.

- A microwave network analyzer makes it possible to measure the time delay and attenuation of a microwave signal propagating through a plasma at atmospheric pressure. These are related to the real and imaginary parts of the plasma index of refraction described by Appleton's equation. From the latter and knowledge of the plasma thickness, one can calculate the plasma electron number density and the electron collision frequency.

- The electron collision frequency is all that one needs to know in order to determine the transport coefficients (diffusion constant, viscosity, thermal conductivity, and electrical conductivity); these allow the plasma to be numerically modeled without further assumptions.

- Since the electron collision frequency is a measured quantity, one need not know the electron energy distribution function, the electron kinetic temperature, or the electron energy-dependent cross section for the collisional process.

Outline

- ✓ Appleton's Equation
- ✓ Experimental Setup
- ✓ Experimental Data
- ✓ Conclusions

Appleton's Equation

As an electromagnetic plane wave propagates in an homogeneous plasma, shown in Figure 1, the complex index of refraction is given by *Appleton's equation,*

$$\bar{\mu}^2 = (\mu - j\chi)^2 = 1 - \frac{\omega_{pe}^2/\omega^2}{C_1 \pm C_2^{1/2}} \qquad \textbf{(1)}$$

Where the constants are given by

$$C_1 = 1 - j\frac{\nu_c}{\omega} - \frac{(\omega_c^2/\omega^2)\sin^2\theta}{2\left[1 - (\omega_{pe}^2/\omega^2) - j\nu_c/\omega\right]^2} \qquad \textbf{(2)}$$

$$C_2 = \frac{(\omega_c^4/\omega^4)\sin^4\theta}{4\left[1 - (\omega_{pe}^2/\omega^2) - j\nu_c/\omega\right]^2} + \frac{\omega_c^2}{\omega^2}\cos^2\theta \qquad \textbf{(3)}$$

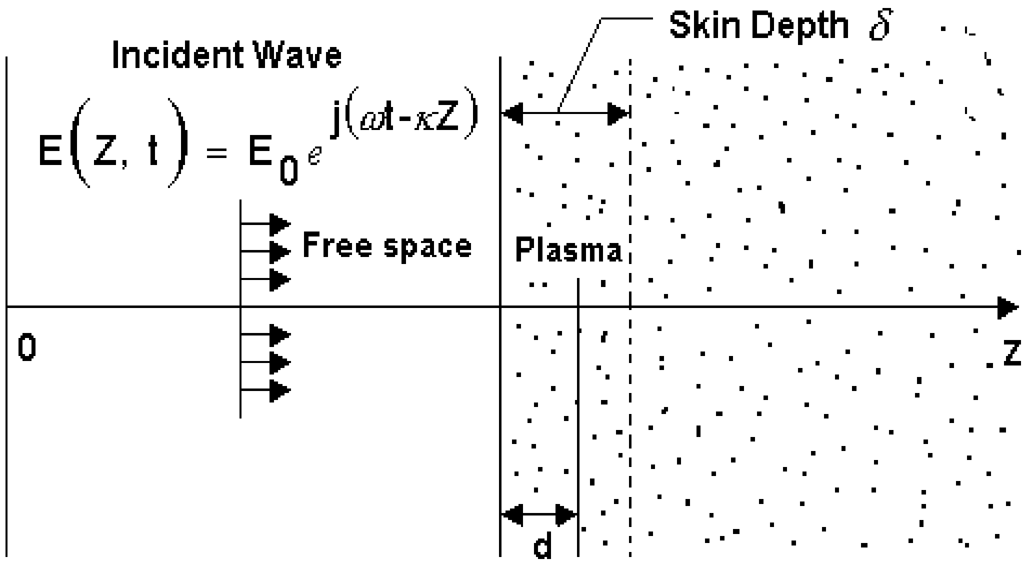
Where ω_{pe} is plasma electron frequency, ν_c is the electron collision frequency, and ω is the microwave frequency.

The propagation is described in terms of the real index of refraction,

$$\mu=\left\{\frac{1}{2}\left(1-\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)+\frac{1}{2}\left[\left(1-\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)^{2}+\frac{\nu_{c}^{2}}{\omega^{2}}\left(\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)^{2}\right]^{1/2}\right\}^{1/2} \quad \textbf{(4)}$$

and the attenuation index ,

$$\chi=\left\{-\frac{1}{2}\left(1-\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)+\frac{1}{2}\left[\left(1-\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)^{2}+\frac{\nu_{c}^{2}}{\omega^{2}}\left(\frac{\omega_{pe}^{2}}{\omega^{2}+\nu_{c}^{2}}\right)^{2}\right]^{1/2}\right\}^{1/2} \quad \textbf{(5)}$$



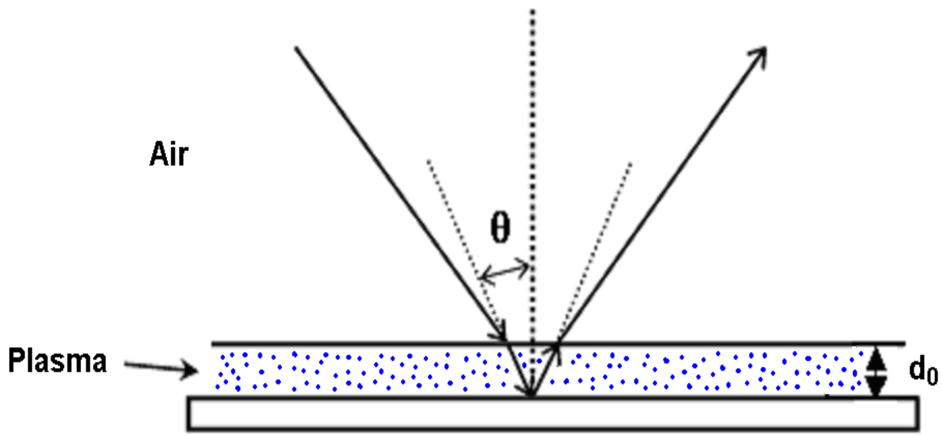


Figure 1: Electromagnetic wave propagating through plasma

Relationship between the Propagation Equation and Appleton's Equation

The propagation constant in the plasma is given by

$$\kappa \equiv \alpha + i/\delta \qquad (6)$$

The real part of the propagation constant, α, is related to the real refractive index by

$$\alpha = \frac{\omega}{c}\mu \qquad (7)$$

The relationship between the attenuation index, χ, and the skin depth, δ, is given by

$$\frac{1}{\delta} = \frac{\omega}{c}\chi \qquad (8)$$

The propagation equation is given by

$$E(z,t) = E_0 e^{j(\omega t - \kappa z)} = E_0 e^{-\frac{z}{\delta}}(\omega t - \alpha z) \qquad (9)$$

Equations for the Attenuation and Phase Shift

- The attenuation as a function of plasma parameters and incident frequency is :

$$dB = 10\log_{10}\left\{\left(\frac{E}{E_0}\right)^2\right\} = 10\log_{10}\left(e^{-\frac{2d}{\delta}}\right) = 10\log_{10}\left((e^{-\frac{2d\omega}{c}\chi}\right) = f(n_e,\ \nu_c,\ \omega,\ d) \quad (10)$$

- The Phase Shift as a function of plasma parameters and incident frequency is :

$$\Delta\varphi = \varphi - \varphi_f = \left(\frac{\omega}{c}\mu - \frac{2\pi}{\lambda}\right)d = g(n_e,\ \nu_c,\ \omega,\ d) \quad (11)$$

In the above two equations d is the propagation distance through plasma, n_e is the electron number density, ν_c is the electron collision frequency, and ω is the frequency of the incident electromagnetic wave.

Experimental Components for Electron Number Density Measurement

- Flat panel plasma generator, UT Plasma Science Laboratory
- Hewlett Packard 8510C vector network analyzer
- RF power supply system, TITAN SERIES™, by Compact Power Company
- 20 dB standard gain horn antenna, 12.4 – 18 GHz, by Advanced Technical Materials Inc.

Schematic of Flat Panel Plasma Reactor

- The upper surface is covered by parallel strip electrodes and the lower electrode is a copper sheet.
- A dielectric panel is located between upper and lower electrodes, the dimensions of which are 30cmX30cm.
- The distance between strip electrodes on the upper surface is 2.5 mm.
- The RF driving frequency is 1-12 KHz and the operating voltage is 3-6 KV.

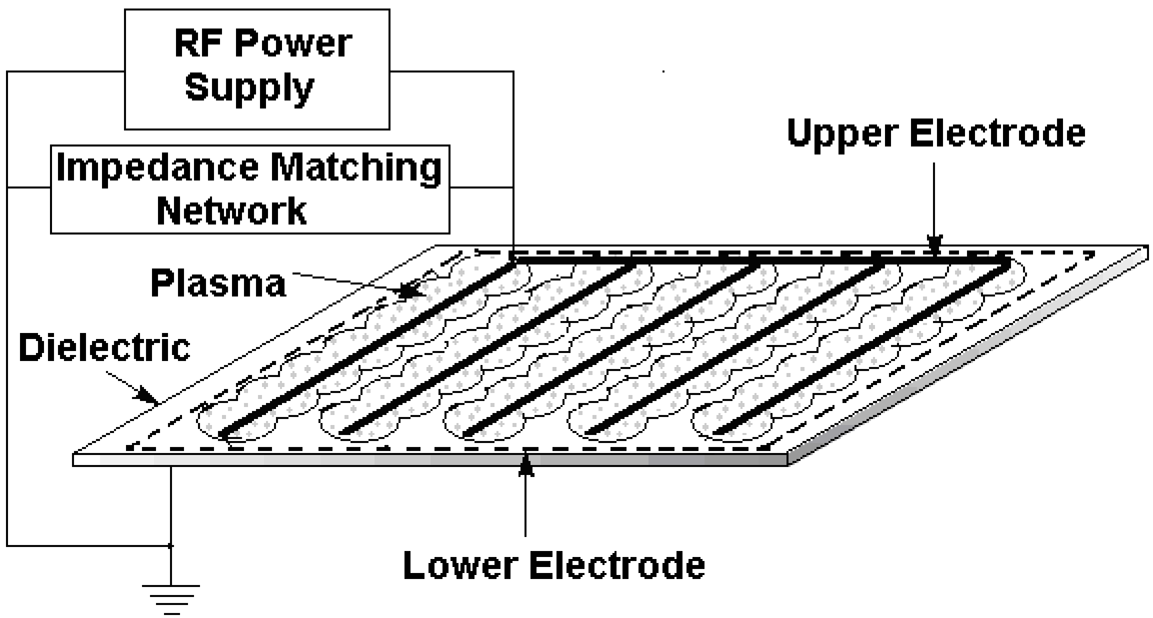
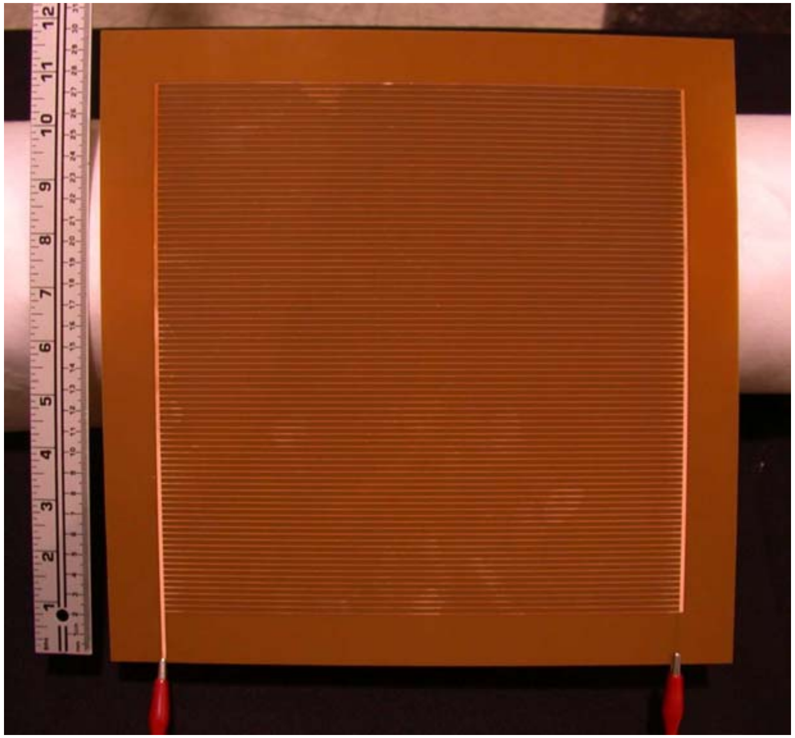
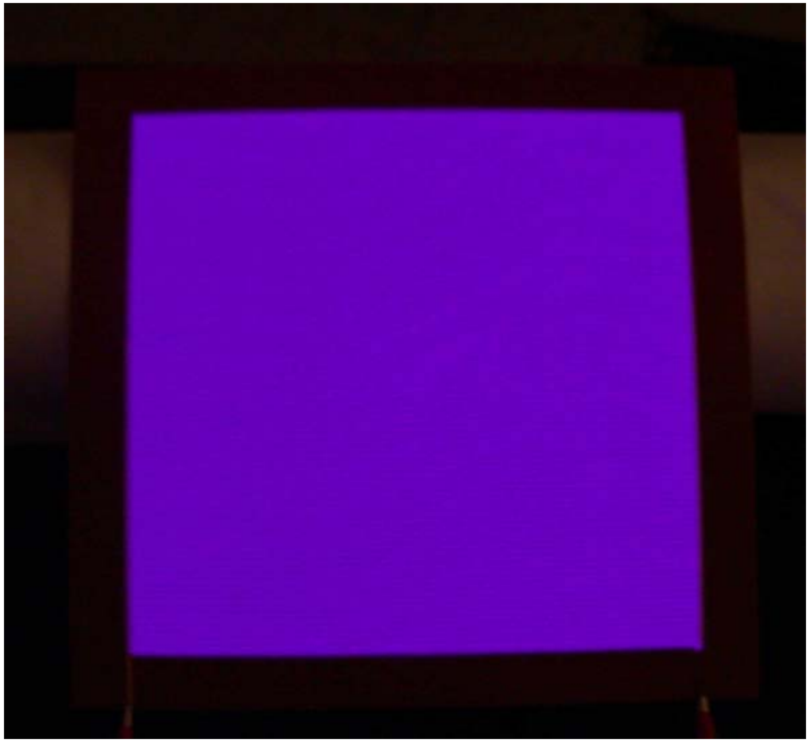


Figure 2: Flat panel reactor



Plasma off



Plasma on

Figure 3: Plasma panel for E-M absorption measurements

The Hewlett Packard (HP) 8510C Network Analyzer System

- Provides the performance to measure the magnitude, phase, and group delay of two-port networks to characterize their linear behavior.
- Has a frequency range 0.045 GHz – 18 GHz
- Has the ability to do time-averaged number density measurement and the potential to do time-resolved measurements.
- Major system components include: 8510C vector network analyzer, 8514A S-parameter set, 8350B signal generator.

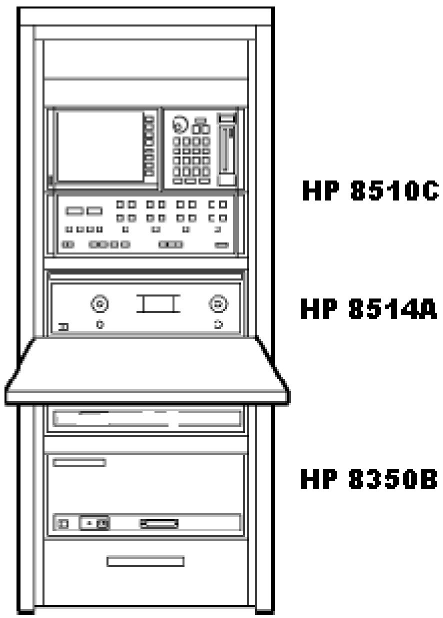


Figure 4: Network Analyzer

Schematic for Experimental Setup

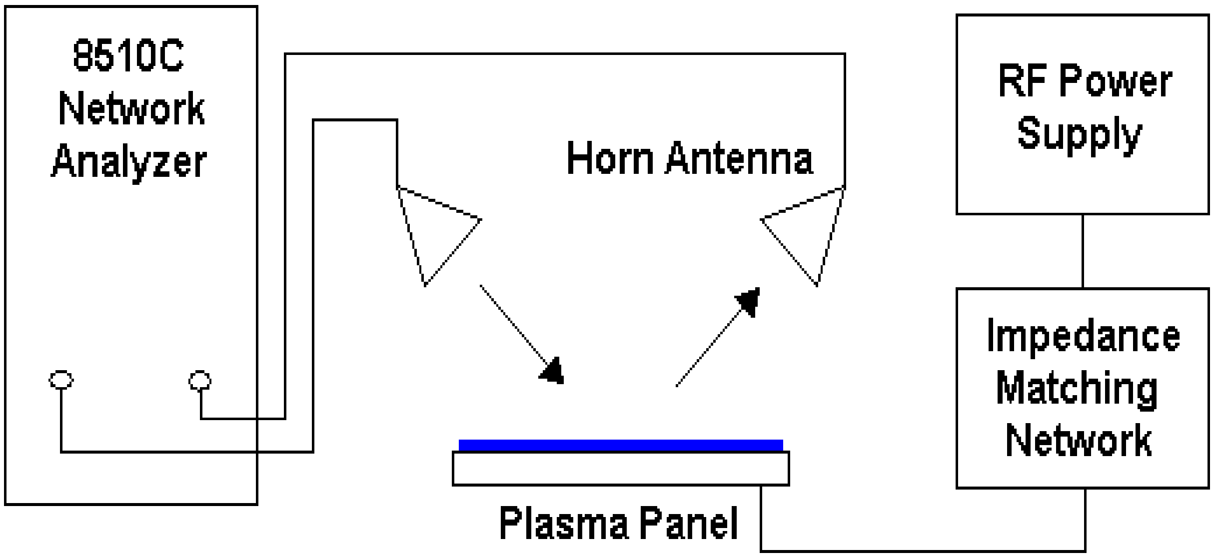


Figure 5: Experimental setup

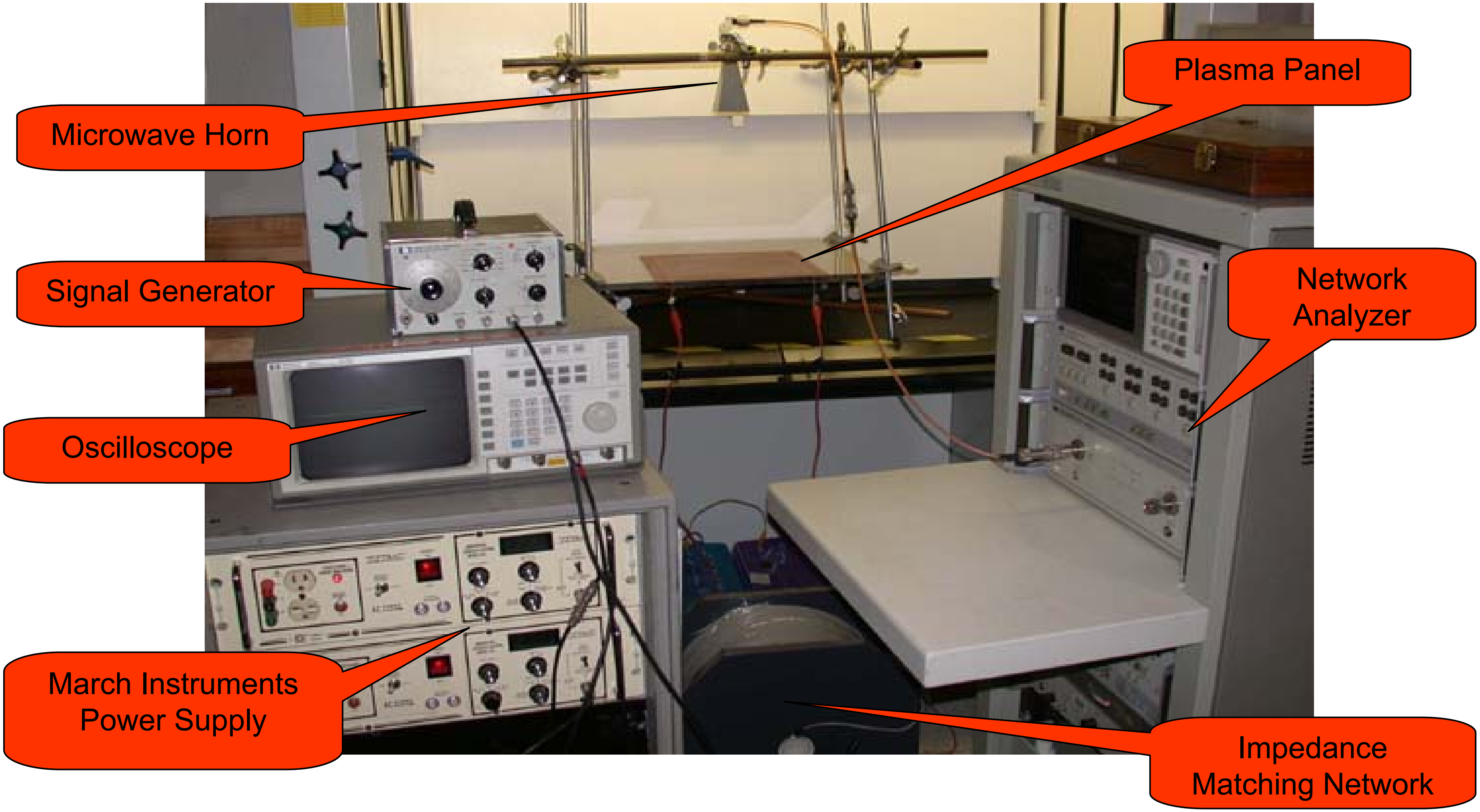
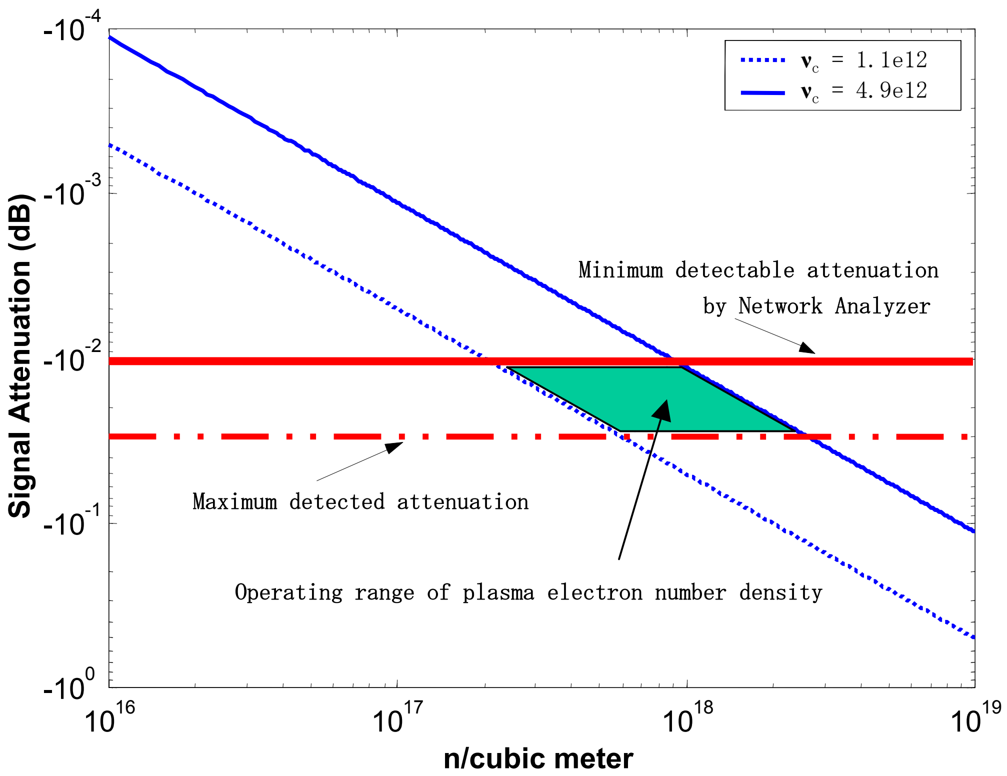


Figure 6: Photograph of the experimental setup

Simulation Result of Attenuation through Thin Plasma Layer by Using (10)



Initial Condition:

ν = 15 GHz

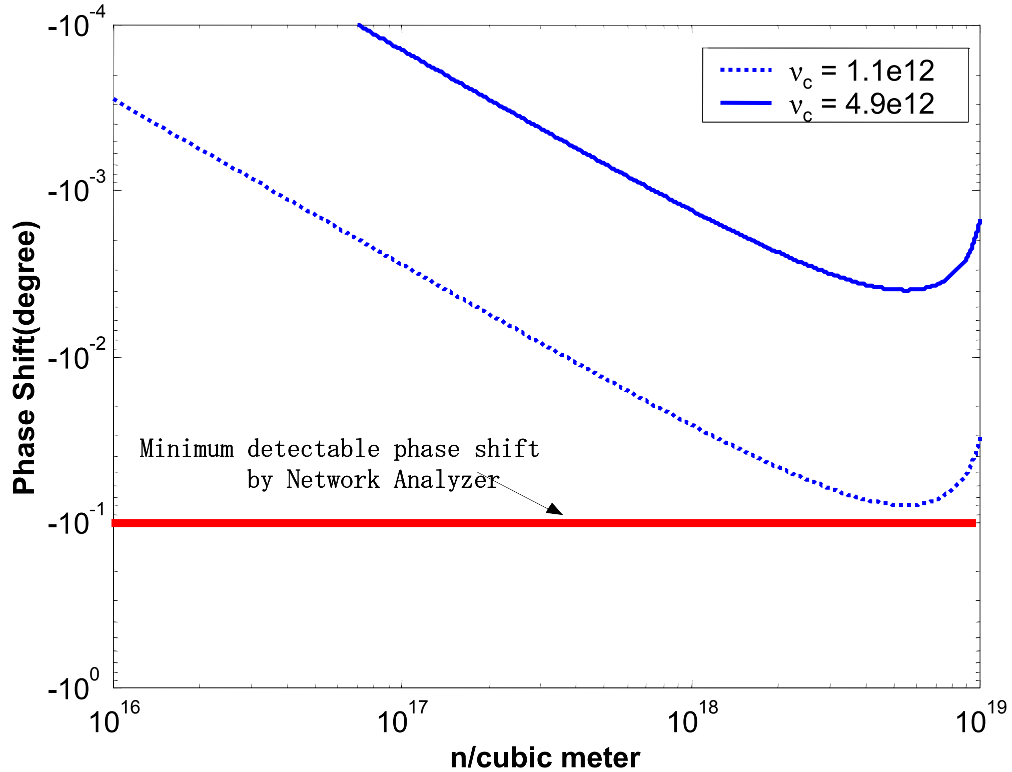
d_0 = 0.3 mm, double reflection

Incident angle = 60^0

$\nu_c = [\,1.1 - 4.9] \times 10^{12}$ Hz

Figure 7: Attenuation as a function of Electron Number Density

Simulation Result of Phase Shift through Thin Plasma Layer by Using (11)



Initial Condition:

ν = 15 GHz

d_0 = 0.3 mm, double reflection

Incident angle = 60^0

$\nu_c = [\,1.1 - 4.9] \times 10^{12}$ Hz

Figure 8: Phase Shift as a function of Electron Number Density

Experimental Data

- Attenuation versus the RF frequency

Table 1: 30^0 Incident Angle and 5 KV

Frequency (KHZ)	2.5	3.7	5	7	8	8.5	9	10	11	12
Attenuation (dB)	0	0	0	0.01	0.02	0.02	0.0	0.01	0	0

- Attenuation versus the RF voltage

Table 2: 8.5 KHz RF Signal Input

	0^0 Incidence	30^0 Incidence	60^0 Incidence
4 KV	0 dB	0.011 dB	0.014 dB
5 KV	0.010 dB	0.018 dB	0.031 dB

Electron Number Density from Plasma Attenuation

- Table 3: the electron number density calculated from the attenuation values shown in Table 1

Incident Angle (degree)	0	30	60
Measured Attenuation (dB)	0	0.011	0.014
Equivalent Plasma Thickness (mm)	0.3	0.35	0.6
Electron Number Density (/cubic meter)	---------	3.8e17 -- 1.7e18	2.8e17 -- 1.2e18

f = 8.5 KHz
V = 4 KV
ν_c = 1.1 GHz – 4.9 GHz

- Table 4: the electron number density calculated from the attenuation values shown in Table 2

Incident Angle (degree)	0	30	60
Measured Attenuation (dB)	0.010	0.018	0.031
Equivalent Plasma Thickness (mm)	0.3	0.35	0.6
Electron Number Density (/cubic meter)	4.0e17 -- 1.8e18	6.2e17 -- 2.7e18	6.2e17 -- 2.7e18

f = 8.5 KHz
V = 5 KV
ν_c = 1.1 GHz – 4.9 GHz

CONCLUSIONS

- We have implemented a microwave diagnostic technique that yields reliable and theoretically well-founded measurements of the time-averaged electron number density and the electron collision frequency in a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) in air.

- This diagnostic technique has been applied to the difficult problem of measuring the electron number density in a flat surface OAUGDP™ in air, the thickness of which is only 0.3 mm. These plasmas are useful to produce EHD effects for subsonic plasma aerodynamics.

- Microwave attenuation at 15 GHz in this plasma was up to 0.03 dB for 60^0 incidence. The phase angle was too small to be observed in this plasma. These data imply an OAUGDP™ electron number density ranging from 2.8×10^{17} to 2.7×10^{18} per cubic meter, assuming elastic electron collision frequencies ranging from 1.1 to 4.9 THz at one atmosphere.

- It is anticipated that thicker plasmas than 0.3 mm will allow both the electron number density and collision frequency to be measured with this technique.

- The network analyzer should also allow the macroscopic drift velocity of the plasma electrons to be measured by the Doppler effect, down to velocities below one meter per second.

REFERENCES RELATING TO MICROWAVE PLASMA DIAGNOSTICS

1.) J. R. Roth, *Industrial Plasma Engineering: Volume I, Principles*. Institute of Physics Publishing, Bristol and Philadelphia 1995, ISBN 0-7503-0318-2, See Chapter 13.

2.) J. R. Roth, *Industrial Plasma Engineering: Volume 2,Application to Nonthermal Plasma Processing*. Institute of Physics Publishing, Bristol and Philadelphia 2001, ISBN 0-7503-545-2, See Chapter 21.

3.) M A Heald and C B Wharton, *Plasma Diagnostics with Microwaves*. Rober E. Krieger Publishing Company 1978, See Chapter 1.