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# Microwave propagation through modulated air plasma

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**Abstract.** When a microwave propagates through a plasma in which electron density and electron collision frequency periodically vary, the propagating wave is modulated in amplitude and phase. An approximate theory is derived to suit the laboratory experimental conditions. Introducing the amplitude and phase difference, the dependence of electron density and electron collision frequency has been derived for different radio frequency modulation and frequency parameter. A scanning double probe technique is used to measure the exact time variation in the plasma parameters at any fixed position during a single cycle of the applied field. Theoretical values agree with those of experiment.

**Keywords.** Plasma microwave; scanning probe; modulation.

## 1. Introduction

When an electromagnetic wave propagates through a plasma whose parameters such as electron density $n$, electron temperature $T_e$ and electron-neutral atom elastic collision frequency $\nu$ change periodically, the amplitude $\mu$ as well as the phase difference $\phi$ of the propagating wave become modulated. Theoretical studies have been made by several workers (Ginzburg and Gurevich 1960; Sodha and Palumbo 1963; Sodha and Sawhney 1968) who considered the interaction of an electromagnetic wave with the time-dependent plasma parameters in ionosphere.

Sarkar and John (1965) and John and Sarkar (1970) have developed only the theory for the amplitude modulation of microwave spacing passing through a varying plasma, produced in a laboratory. Varshney and Sakuntala (1977) have developed an improved theoretical model different from that derived by John and Sarkar (1970). It is essential that the theory should accurately describe experimental conditions. In order that the theoretical results apply to the laboratory plasma, the results of an earlier work has been made use of (John and Sarkar 1970; Kumar *et al* 1971). To establish a time-dependent variation in $n$ and $\nu$, the amplitude modulated radio frequency (RF) between 100 Hz and 10 kHz has been applied to dry air in a cylindrical discharge tube at a pressure $< 5$ torr. The available RF power is 500 W at 10 MHz. Chandra (1972) has also considered only amplitude modulation neglecting the phase relation in $n$ and $\nu$. In this paper a simple theoretical model is worked out which includes phase modulation on the propagating wave.

## 2. Simplified theoretical model

The propagating wave is assumed to be weak so that the rate constants for inelastic collisions in the plasma are not significantly perturbed but they are considered strong enough to impose a variation in $T_e$, $n$ and $\nu$. The theoretical model lacks sophistication since many assumptions have to be made. Attachment and recombination losses have been ignored. Thus the one-dimensional treatment has been extended only to include the dependence of the microwave electric field on amplitude modulation, phase change and $\nu$. The energy balance equation is solved for $n$ and $\nu$ which depend on $T_e$. The dependence of variation in $n$ and $\nu$ with the index of modulation $M$ of the exciting RF field has been derived from coupled equations obtained for the ratio of varying and steady components of the plasma

$$M = E_{\max} - E_{\min} / (E_{\max} + E_{\min}),$$

where $E$ refers to the envelope of the RF field (figure 1). The general energy equation of the RF modulated plasma can be written as

$$n \cdot P(t) = n \frac{dQ(t)}{dt} + n \delta \nu [Q(t) - Q(0)] + E_f \frac{dn}{dt} + Q_0 D \nabla^2 n + E_f R n^2. \quad (1)$$

where (1) is $n \cdot P_1 (1 + M \cos \Omega\, t)^2$ gives the total time-dependent power absorbed in the plasma from the exciting RF field of power $P_1$ (Seely 1958). $\Omega$ is the modulating frequency which was varied between 100 Hz to 10 kHz and $n$ is the electron density at any instant $t$. The first term on the right hand side of (1) gives the energy necessary to increase the random energy $Q(t)$ of the electrons at any time $t$. The second term is the energy lost in elastic electron-atom collisions, $Q_0$ is the average electron energy which is of the order of the thermal energy $kT \simeq 1{\cdot}0$ eV. $\delta$ is the fractional energy loss in an elastic collision and $\nu(t)$ is the electron-molecule collision frequency at any instant $t$. The third term is the energy needed to create new electron-ion pairs, $E_f$ being the ionisation energy, generally of the order of 10 eV (von Engel 1965). The fourth term is the energy loss due to diffusion of the wall and the fifth term indicates the energy lost by electron-ion recombination; $D$ and $R$ are the coefficients of diffusion and recombination respectively. Since the gas pressure is low, the recombination can be neglected (Sayer 1938). Under steady state conditions the net space charge is negligible.

The variation in $n(t)$ and $\nu(t)$ may be represented by

$$n(t) = n_0 + n_1 \cos (\Omega t + \phi) = n_0 [1 + \alpha \cos (\Omega t + \phi)], \quad (2)$$

$$\nu(t) = \nu_0 + \nu_1 \cos (\Omega t + \phi) = \nu_0 [1 + \beta \cos (\Omega t + \phi)], \quad (3)$$

where $n_0$ and $\nu_0$ are the steady components, $n_1$ and $\nu_1$ are the maximum variation in $n$ and $\nu$ respectively. $\alpha = n_1/n_0$ and $\beta = \nu_1/\nu_0$ are the amplitude modulations in $n$ and $\nu$ of the plasma. $\phi$ is the phase difference between the exciting field and the time-dependent plasma parameters. To simplify the analysis to a first approximation, the phase modulation impressed on propagating wave has been taken to be the same as that for $n$ and $\nu$ with the exciting RF field. It has been assumed that $\nu \gg \Omega$ and that the RF field is uniform throughout the plasma. Putting $Q(t)-Q_0=x$, equation (1) reduces to

$$n\cdot P_1(1+M\cos\Omega t)^2=n\frac{dx}{dt}+nx\delta\nu+Q_0D\nabla^2 n. \tag{4}$$

Let $$x=A\cos(\Omega t-\chi_1)+B\cos(2\Omega t-\chi_2), \tag{5}$$

where $A$ and $B$ are constants and $\chi_1$ and $\chi_2$ the phase angles.

Substituting $n$, $\nu$ and $x$ from (2), (3) and (5) into (4) and equating the like terms of the time-dependent parts, the following coupled equations are obtained

$$\Big\{2MP_1+P_1\alpha\left(1+\frac{3M^2}{4}\right)\cos\phi-\Omega A\sin\chi_1-\Omega B\alpha\sin(\phi+\chi_2)-$$
$$\delta\nu_0 A\cos\chi_1-\tfrac{1}{2}(\delta\nu_0 B)(\alpha+\beta)\cos(\phi+\chi_2)-\frac{Q_0}{n_0}(\cos\phi).D\nabla^2 n_1\Big\}=0, \tag{6}$$

$$\Big\{-P_1\alpha\left(1+\frac{M^2}{4}\right)\sin\phi+\Omega A\cos\chi_1+\Omega B\alpha\cos(\phi+\chi_2)-\delta\nu_0 A\sin\chi_1-$$
$$\tfrac{1}{2}(\delta\nu_0 B)(\alpha+\beta)\sin(\phi+\chi_2)+\frac{Q_0}{n_0}(\sin\phi)\cdot D\nabla^2 n_1\Big\}=0, \tag{7}$$

$$\{-\tfrac{1}{2}(M^2P_1)+MP_1\alpha\cos\phi-2\Omega B\sin\chi_2-\tfrac{1}{2}(A\Omega\alpha)\sin(\chi_1-\phi)-$$
$$\delta\nu_0 B\cos\chi_2-\tfrac{1}{2}(\delta\nu_0 A)(\alpha+\beta)\cos(\phi-\chi_1)\}=0, \tag{8}$$

$$\{-MP_1\alpha\sin\phi+2\Omega B\cos\chi_2+\tfrac{1}{2}(\Omega A\alpha)\cos(\phi-\chi_1)-\delta\nu_0 B\sin\chi_2+$$
$$\tfrac{1}{2}(\delta\nu_0 A)(\alpha+\beta)\sin(\phi-\chi_1)\}=0, \tag{9}$$

$$\tfrac{1}{4}(M^2P_1\alpha)\cos\phi+\Omega B\alpha\sin(\phi-\chi_2)-\tfrac{1}{2}(\delta\nu_0 B)(\alpha+\beta)\cos(\phi-\chi_2)=0, \tag{10}$$

$$-\tfrac{1}{4}(M^2P_1\alpha)\sin\phi+\Omega B\alpha\cos(\phi-\chi_2)+\tfrac{1}{2}(\delta\nu_0 B)(\alpha+\beta)\sin(\phi-\chi_2)=0, \tag{11}$$

$$\sin\chi_2(\cos 2\phi)-\cos\chi_2\sin 2\phi=0. \tag{12}$$

Taking the modulation frequency parameter $K=\delta\nu_0/\Omega$, the solution for the above set of equations are

$$\chi_2=2\phi, \tag{13}$$

$$\cot\phi=\tfrac{1}{2}[K(\alpha+\beta)]+\{[\tfrac{1}{2}(K(\alpha+\beta))]^2+1\}^{\frac{1}{2}}, \tag{14}$$

$$B=\frac{M^2P_1}{2\Omega}\sin 2\phi, \tag{15}$$

$$\cot \chi_1 = \frac{\{(2MP_1K/\Omega) + (P_1\alpha/\Omega)\left[K\left(1+\frac{3M^2}{4}\right)\cos\phi + \left(1+\frac{M^2}{4}\right)\sin\phi\right]}{\{(2MP_1/\Omega) + B\alpha[K\cos 3\phi - \sin 3\phi] - (P_1\alpha/\Omega)\left[K\left(1+\frac{M^2}{4}\right)\sin\phi\right.}$$

$$\frac{-B\alpha\,[K\sin 3\phi + \cos 3\phi] - \tfrac{1}{2}\,[KB(\alpha+\beta)]\,[K\cos 3\phi - \sin 3\phi]\}}{\left.\left(1+\frac{3M^2}{4}\right)\cos\phi\right] - \tfrac{1}{2}[BK(\alpha+\beta)](K\sin 3\phi - \cos 3\phi)]\}}, \quad (16)$$

$$A = \frac{(2MP_1/\Omega) + (P_1\alpha/\Omega)[1+(3M^2/4)]\cos\phi - B\alpha\sin 3\phi - \tfrac{1}{2}[BK(\alpha+\beta)]\cos 3\phi}{K\cos\chi_1 + \sin\chi_1} \quad (17)$$

$$(M^2P_1/2\Omega) + (MP_1\alpha/\Omega)\cos\phi - 2B\sin 2\phi - (A\alpha/2)\sin(X_1-\phi) -$$

$$KB\cos 2\phi - \tfrac{1}{2}\,[K(\alpha+\beta)\,A\cos(\phi - X_1) = 0, \quad (18)$$

$$-(MP_1\alpha/\Omega)\sin\phi + 2B\cos 2\phi + (A\alpha/2)\cos(\phi - X_1) - KB\sin 2\phi +$$

$$\tfrac{1}{2}[K(\alpha+\beta)]\,A\sin(\phi - X_1) = 0. \quad (19)$$

It can be seen from (6) and (7) that the rate-dependence in the diffusion term occurs in $n_1$ which means that the diffusion depends on the space variation. Since $n_1 \ll n_0$ the effect of diffusion on the time-dependent variation in $n$ has been taken to be negligible. Owing to the complex nonlinear behaviour of $\alpha$ and $\beta$, their explicit solutions could not be obtained, and have been estimated by the iterative method of computation of (18) and 19). Thus Maxwell's equations in terms of a fluctuating conductivity of the plasma have been solved and $\mu$, the modulation impressed on the propagating microwave of frequency ($\omega$) has been derived.

The change in the plasma conductivity owing to the small variation in $n$ and $\nu$ can be taken as

$$\triangle\sigma = \sigma_0[(n_1/n_0) - (\nu_1/(\nu_0+i\omega))]\cos(\Omega t + \phi), \quad (20)$$

where $\sigma_0$ is the steady component of the plasma conductivity, thus,

$$\sigma = \sigma_0\,[1 + a\cos(\Omega t + \phi)], \quad (21)$$

where $$a = \alpha - [\nu_1/(\nu_0+i\omega)] = \alpha - \left[1 \Big/ \left(\frac{1}{\beta} + \frac{i\omega}{\nu_1}\right)\right]; \quad \sigma_0 = n_0 e^2/[m\epsilon_0(\nu_0+i\omega)]. \quad (22)$$

Following the analysis given by John (1968) and John and Sarkar (1970) the wave equation for the propagating field $E$ in the $Z$ direction through plasma is given by

$$\partial^2 E/\partial z^2 = -(\epsilon_0\,\mu_0\,\omega^2/C^2)\,E_0 + (4\pi\,\mu_0\,i\omega\sigma_0/C^2)\,E_0. \quad (23)$$

$\epsilon_0$ is the dielectric permittivity, $\mu_0$ is the magnetic permeability and $C$ is the velocity of light. $E_0$ is the steady electric field of the propagating wave.

Normalising the above equation by dividing it by an arbitrary field and assuming that $(\epsilon_0\mu_0)^{1/2}\ \omega z/C=Z$ and also that the propagating wave is amplitude-modulated at a frequency $\Omega$, the three frequency components of the propagating wave through the plasma are given by $\omega$, $\omega+\Omega$ and $\omega-\Omega$. With the boundary conditions, $E_0=A_0$, a constant at $Z=0$ and $E_0=0$ at $Z=\infty$, the solution for the propagating wave as a whole can be obtained by the successive approximation method for the three frequency components. The resulting electric vector associated with the propagating electromagnetic wave with the assumed phase change $\phi$ can be represented by, with $\beta_0=(1-4\pi\ i\sigma_0/\epsilon_0\ \omega)^{1/2}$,

$$E=A_0 \exp i\,(\omega t-\beta_0 Z)\left[1+\frac{2\pi a\, Z\, \sigma_0}{\epsilon_0\, \omega\, \beta_0}\cos\,(\Omega t+\phi)\right]. \tag{24}$$

Taking $Z$ to represent the length of the plasma through which the electromagnetic wave passes, (24) gives the electromagnetic wave modulated in amplitude and phase. The impressed amplitude modulation on the propagating wave is given by

$$\mu=\frac{2\pi\ a\ Z\sigma_0}{\epsilon_0\ \omega\ \beta_0}=\frac{\pi(\omega_p^2/\omega^2)\ (Z/\lambda)}{[1+(\nu_0/\omega)^2]^{1/2}}\left\{\left[a-\frac{\beta}{1+(\omega/\nu_0)}\right]^2+\left[\frac{\beta(\nu_0/\omega)}{1+(\nu_0/\omega)^2}\right]^2\right\}^{1/2}. \tag{25}$$

Here $\sigma_0$ represents only the real component of the plasma conductivity where $\omega_p$ is the plasma frequency and $\lambda$ is the free space wavelength of the electromagnetic wave

$$\omega_p=(4\pi\ n_c\ e^2/m)^{1/2}.$$

## 3. Experimental method

The modulation frequency $\Omega$ of the RF field and $M$ can be experimentally controlled. From the gas pressure and double probe characteristics of Johnson and Malter (1950), the steady components of $n_1$ $T_e$ and $\nu_0$ are initially estimated. $\nu_0$ has also been derived from microwave absorption in plasma. The plasma is maintained in 4·0 cm diameter glass tube fitted with external electrodes and filled with dry air at pressures between 0·2 torr and 2·0 torr. An RF field of 10 MHz, generated by a negative resistance push-pull type oscillator, is applied to two copper rings forming the external electrodes of the discharge tube. The RF field is amplitude-modulated by superimposing a variable audio frequency between 100 Hz and 10 kHz. A reflex Klystron power supply which delivers a maximum of 20 mW power at frequency range between 8·5 to 9·66 GHz is used for the microwave generation. Two probes made of tungsten wire of 0·1 cm diameter are fixed in the discharge tube with their tips about 1·5 cm from the wall of the tube. The length of the probe exposed to the plasma is only 0·1 cm, the remaining surface of the probe is in a glass envelope. The frequency of the propagating microwave is kept constant at $\omega/2\pi=9{\cdot}66$ GHz. The experimentally observed steady state values of $n_0 \simeq 10^{11}$ cm$^{-3}$. $T_{e0}\simeq 10^4$K and the percentage of ionisation is found to be of the order of $10^{-6}$ for the air pressures studied. $\nu_0$ found to be of the order of $10^{10}$ Hz. Characteristics of $\mu$, have been displaced on an oscilloscope and $\nu_0$ is calculated from the measured $n$. From the steady components $n_0$ and $T_e$, $\nu_0$ can be estimated since $\nu_0 = v_r/\lambda_0$, where $\lambda_0$ is the electron mean free path at the gas pressure $p$ in torr. The random velocity $v_r$ of the electrons at $p$ is given by

$$v_r = (8\, k\, T_e/\pi m)^{1/2}$$

$k$ is the Boltzmann constant and $m$ is the electron mass. If $\lambda_1$ is the electron m.f.p. at 1 torr then $\lambda_0 = \lambda_1/p$ values are taken from von Engel (1965).

The computed values have been obtained for a variation of $M$ from 0·1 to 1·0 (10% to 100% modulation). The frequency parameter $K$ for RF modulation is varied from 2 to 100 and the microwave modulation is found for a variation in $\nu_0/\omega$ between 0·1 to 50. Figure 1 shows the theoretical variation of $\mu$ with $M$ for different $\nu_0/\omega$. It is evident that the impressed modulation on the propagating wave increases with the decrease in $\nu_0/\omega$.

Figure 2 shows the theoretical results of $\alpha$ and $\beta$ as a function of $K$ for any $M$ and as a function of $M$ for any $K$ of the modulated field. The variation in $\alpha$ and $\beta$ as a function of $K$ for any $M$ is slight, though there is a general linear increase in $\alpha$ and $\beta$ with $M$ for a particular $K$. The computed variation of $\mu = F(K, \phi)$ for different values of $M$ are also found. For $K=5$, curves b, c and d show the variation of $\alpha$, $\beta$ and $\mu$ with $M$ respectively. Curve a gives the variation of $\phi$ with $K$ for constant $M$. The

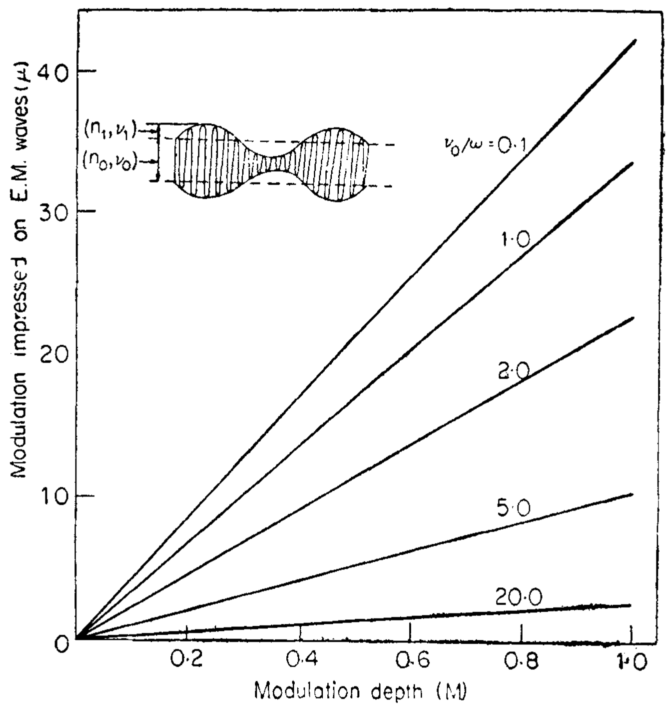


**Figure 1.** Calculated variation of the impressed modulation $\mu$ on the microwave propagating through RF modulated plasma with the RF modulation depth $M$ at different $\nu_0/\omega$ values.

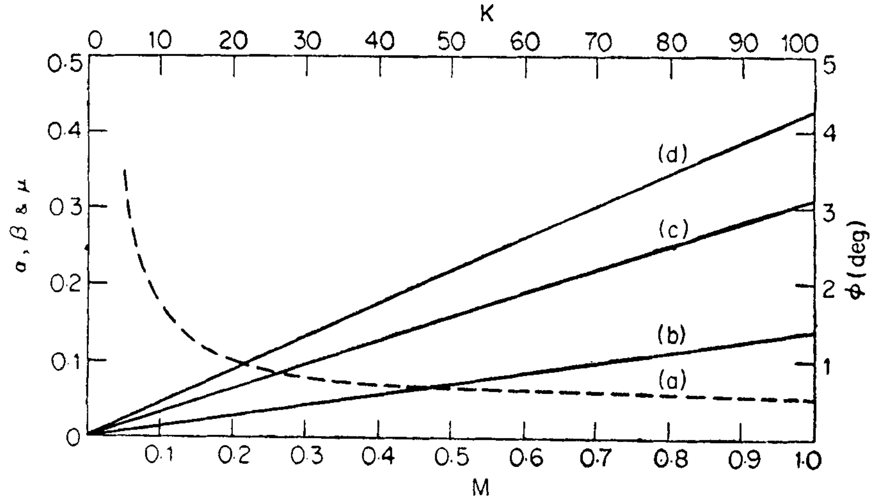


**Figure 2.** Variation of $\alpha$, $\beta$ and $\mu$ for various values of $M$ and modulation frequency parameter $K$ and variation of the phase angle $\phi$ with $M$ and $K$, for $Z=25{\cdot}0$ cm and $(\omega_p/\omega)^2=0{\cdot}02$.

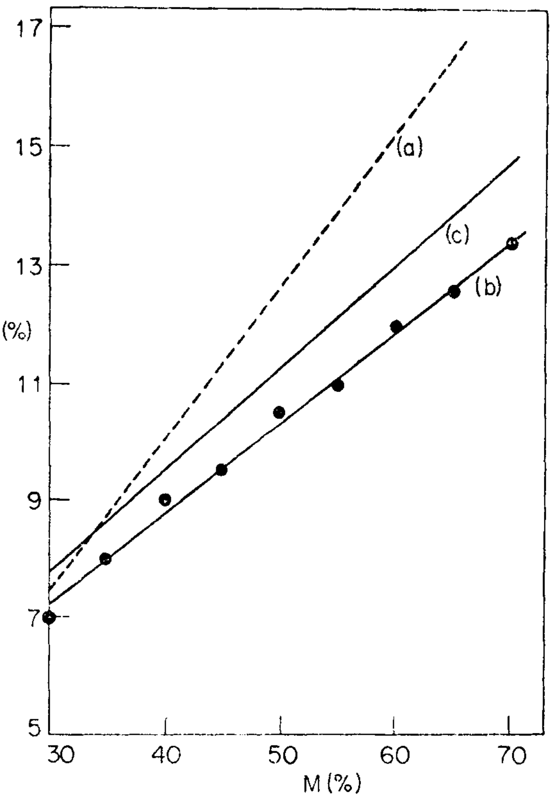


**Figure 3.** Calculated and experimental values of % $\mu$ with %$M$ for $p = 0{\cdot}2$ torr, $Z=25{\cdot}0$ cm and $(\omega_p/\omega)^2=0{\cdot}05$.

amplitude modulation is found to be independent of the phase angle considered here. However $\phi$ and $\mu$ vary strongly with $K$ and $M$. For constant $K$ and $\phi$, $\mu$ increases with $M$. Variation of $K$ with $\phi$ at constant $M$ results in a slow decrease.

In figure 3, curve a shows the calculated values of the percentage modulation $\mu$ % with $M$ % given by Kumar *et al* (1971) who considered only amplitude modulation in $\alpha$ and $\beta$ neglecting the phase variation. Curve c gives the theoretical variation of $\mu$ with $M$ including the phase difference in $n$ and $\nu$ as presented in the given theory.

Curve b shows the experimental values derived by double probe measurements. These experimental values agree with the measured values by John (1968). For a particular $M$ say 50%, the experimental value of $\mu$=10·2% while calculated value including phase modulation gives $\mu$=11·3%. Only amplitude modulation gives $\nu_0$=12·6%. Thus values based on the theory presented are nearer to the experimental values; showing that the microwave gets strongly modulated both in amplitude and in phase while propagating through a plasma. Experimental results based on double probe characteristics virtually measure only the steady state components $n_0$ and $T_{e_0}$ and hence $\nu_0$. This may be the cause for the observed discrepancy between the experimental and theoretical values. However, the trend of variation is the same in theory and experiments.

## 4. Scanning probe technique

A scanning probe technique is developed and is used to measure the probe current-voltage characteristics accurately at any point during a single cycle of the modulated applied field. The periodic variation in $n$ and $T_e$ are observed by full scanning over the cycle and the maximum variation over the average values of $n_0$ and $\nu_0$ have been obtained. Figure 4 shows the general block diagram of the experimental arrangement. By applying sweep pulses to the probes, current-voltage characteristics can be obtained. Adjusting the rate constants of the RF modulation and probe sweep pulses, it is possible to trace the current-voltage characteristics repeatedly, at any fixed point of the cycle. Between two successive minima of the modulated half cycle, the sweep pulse scans along the wave at eight places, four along the rising part and four along the decreasing part of the half cycle. Similarly scanning is done during the negative

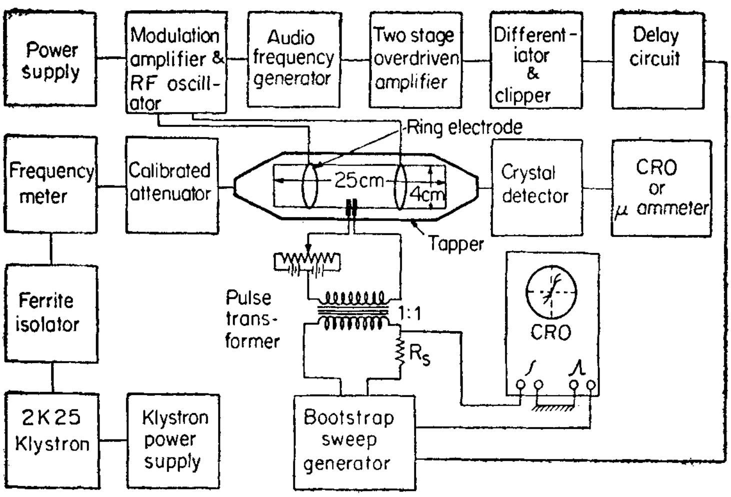


**Figure 4.** Block diagram of the experimental arrangement.

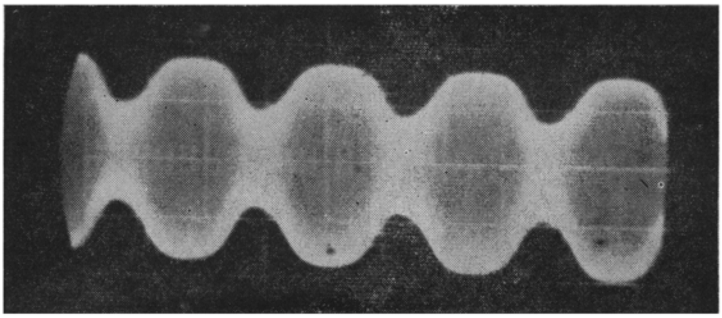

**Figure 5.** Plasma excited by the modulated RF power (envelope) displayed on an oscilloscope.

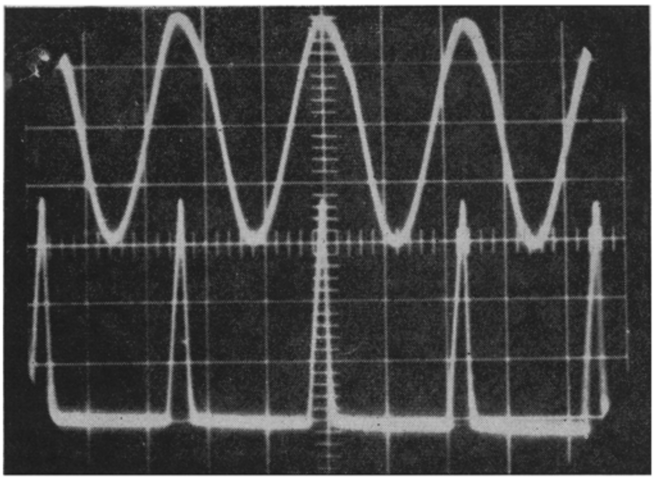

**Figure 6.** Modulating acoustic pulse (without RF plasma) and the sweep pulse applied to the scanning probes at the apex of the modulating pulse, displayed on the double beam oscilloscope.

**Table 1.** Measured values of $n_0$, $n_1$, $\nu_0$ and $\nu_1$ at different gas pressures $p$ and % modulation $M$.

| $p$ torr | Average values without modulation | | $M=30\%$ | | $M=40\%$ | | $M=50\%$ | | $M=60\%$ | | $M=65\%$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $n_0\times10^{10}$ | $\nu_0\times10^{9}$ | $n_1\times10^{9}$ | $\nu_1\times10^{8}$ | $n_1\times10^{9}$ | $\nu_1\times10^{8}$ | $n_1\times10^{9}$ | $\nu_1\times10^{8}$ | $n_1\times10^{9}$ | $\nu\times10^{8}$ | $n_1\times10^{9}$ | $\nu\times10^{8}$ |
| 2·0 | 1·9 | 4·16 | 0·9 | 4·6 | 1·2 | 5·6 | 1·4 | 6·9 | 1·8 | 8·2 | 2·0 | 8·7 |
| 1·5 | 2·4 | 3·24 | 1·2 | 3·8 | 1·7 | 4·6 | 1·9 | 5·4 | 2·4 | 6·4 | 2·7 | 7·0 |
| 1·0 | 3·3 | 2·28 | 1·8 | 2·9 | 2·4 | 3·4 | 2·8 | 4·1 | 3·4 | 3·7 | 3·9 | 5·1 |
| 0·5 | 4·6 | 1·20 | 2·7 | 1·6 | 3·7 | 1·9 | 4·1 | 2·2 | 5·0 | 2·7 | 5·6 | 2·8 |
| 0·2 | 5·85 | 0·50 | 3·6 | 0·7 | 4·9 | 0·8 | 5·5 | 0·9 | 6·5 | 1·1 | 7·2 | 1·2 |

**Table 2.** Experimental and theoretical values of $\alpha$ and $\beta$ for various values of % modulation $M$ and pressures $p$ (torr) $\omega/2\pi=9{\cdot}66\times10^9$ Hz and $Z=25$ cm.

| $M(\%)$ | | 2·0 | | 1·5 | | 1·0 | | 0·5 | | 0·2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ |
| 30 | Experimental | 0·042 | 0·110 | 0·050 | 0·117 | 0·054 | 0·127 | 0·059 | 0·133 | 0·062 | 0·140 |
| | Theoretical | 0·041 | 0·095 | 0·046 | 0·100 | 0·051 | 0·105 | 0·056 | 0·110 | 0·061 | 0·115 |
| 40 | Experimental | 0·063 | 0·135 | 0·071 | 0·142 | 0·073 | 0·150 | 0·080 | 0·159 | 0·084 | 0·160 |
| | Theoretical | 0·055 | 0·125 | 0·060 | 1·130 | 0·065 | 0·135 | 0·070 | 1·140 | 0·075 | 0·145 |
| 50 | Experimental | 0·074 | 0·160 | 0·079 | 0·166 | 0·085 | 0·180 | 0·089 | 0·184 | 0·094 | 0·180 |
| | Theoretical | 0·069 | 0·156 | 0·074 | 0·161 | 0·079 | 0·166 | 0·084 | 0·171 | 0·089 | 0·176 |
| 60 | Experimental | 0·095 | 0·198 | 0·100 | 0·198 | 0·104 | 0·206 | 0·109 | 0·215 | 0·111 | 0·220 |
| | Theoretical | 0·083 | 0·186 | 0·088 | 0·191 | 0·093 | 0·196 | 0·098 | 0·201 | 0·103 | 0·206 |
| 65 | Experimental | 0·105 | 0·210 | 0·112 | 0·216 | 0·018 | 0·224 | 0·120 | 0·234 | 0·123 | 0·240 |
| | Theoretical | 0·089 | 0·200 | 0·094 | 0·205 | 0·099 | 0·210 | 0·104 | 0·215 | 0·109 | 0·220 |

half of the cycle. Thus for any modulation depth, four readings can be obtained for a fixed point. Hence the variation in $n$ and $\nu$ over the average values are estimated accurately for one complete cycle of the RF field. Figure 5 shows the modulated RF power used, to excite the plasma as displayed on an oscilloscope. Figure 6 shows the modulating acoustic pulse (without RF plasma) and the variability of the sweep pulse applied to the probes to scan any particular position during the modulating wave. Both pulses are shown on the double beam oscilloscope.

## 5. Results and discussion

The results presented to indicate the variation in $n$ and $T_e$, measured by the scanning probe, cover only the maximum values ($n_1$ and $\nu_1$ at the apex of the modulating cycle—figure 6). Experimentally observed $n_0$, $n_1$, $\omega_p$ and $\nu_0$ are given in table 1, for different $M$ and $p$ values. Table 2 gives the observed values of $\alpha$ and $\beta$ in the range of $p$ and $M$ studied. The theoretical solution for the impressed modulation on the microwave given by (25), is applicable only to a particular gas pressure $p$. For a given value of $p$, $n_0$, $\omega_p$ and $\nu_0$ remain constant so that $\alpha$ and $\beta$ depend on the variation in $M$ only. However, if $p$ is varied, $n_0$, $p$, $n_0$, $T_{e_0}$ and $\nu_0$ vary and hence for a fixed value of $M$, there will be a variation in $\alpha$ and $\beta$. Thus $\alpha$ and $\beta$ represent another set of values at the given $M$ when $p$ is different. These values of $\alpha$ and $\beta$, naturally now vary (at the changed pressure), when $M$ is varied. Theoretical values of $\mu$ need incorporating variable values of $\omega_p$, $\nu_0$ and $\alpha$ and $\beta$ when $p$ is changed. For theoretical computation, $\mu$ can be obtained by varying only one of the three factors $\omega_p/\omega$, $\nu_0/\omega$ and $\alpha$ and $\beta$, keeping the other two parameters constant. Theoretically it is not possible to assess the exact variation in $\alpha$ and $\beta$ with $p$. Experiments indicate a 10% variation in the plasma parameters corresponding to a pressure change of 0·5 torr. The calculated pressure corrections are also shown in table 2. In computing the theoretical modulation a general 10% variation in the plasma parameters is considered with the pressure change of 0·5 torr for the whole range of pressures studied. For any given applied RF field $n_0$ decreases with increasing $p$ and $T_e$ increases with decreasing $p$. Whereas $\nu_0$ increases with increasing $p(\nu_0 \propto p\sqrt{T_e})$.

Figure 7 shows the dependence of $\mu$ with $M$ for different $p$ at constant RF amplitude voltage (35 V) and the microwave frequency (9·66 GHz). It is seen that the experimental values agree well with the theoretical values corrected for $p$. The theoretical variation in $\mu$ with $M$ is linear but the experimental results deviate from linearity for $M \geqslant 60$. This may be due either to the rapid increase in the experimentally observed values of $\alpha$ and $\beta$ for higher $M$ whereas the theory assumes a uniform variation (table 2) or that the phase may be changing rapidly for higher modulated power. It can be concluded that the amplitude and phase modulation of a propagating microwave through a laboratory produced plasma in air, depends on the time dependent variation in the plasma parameters and the pressure of the gas, for a given microwave frequency. $\mu$ increases with increase in modulation index and electron density and decreases with the increase in gas pressure.

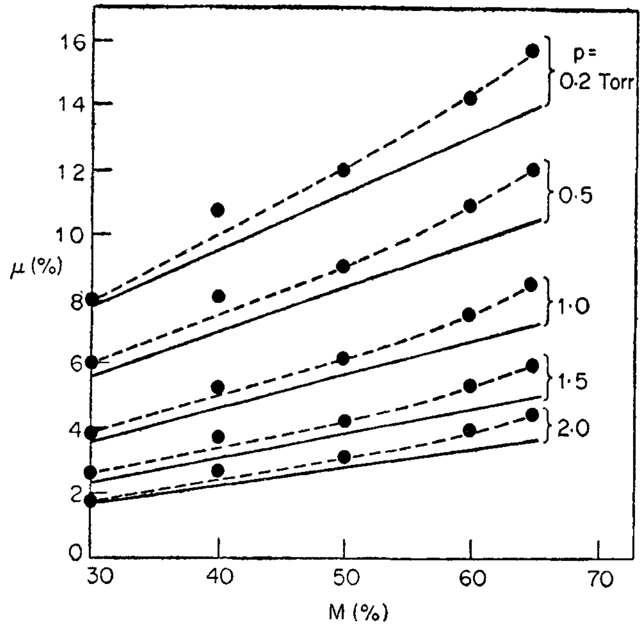


**Figure 7.** Theoretical (solid lines) and experimental (dotted lines) values of $\%\mu$ with $\% M$ for various values of $p$. $Z=25{\cdot}0$ cm and $\Omega/2\pi=600$ Hz.

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