PRAMANA
— journal of
physics

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Vol. 65, No. 2
August 2005
pp. 311–321

Excitation of surface plasma waves over corrugated slow-wave structure

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MS received 9 August 2004; revised 16 November 2004; accepted 4 February 2005

Abstract. A microwave propagating along vacuum–dielectric–plasma interface excites surface plasma wave (SPW). A periodic slow-wave structure placed over dielectric slows down the SPW. The phase velocity of slow SPW is sensitive to height, periodicity, number of periods, thickness and the separation between dielectric and slow-wave structure. These slow SPW can couple the microwave energy to the plasma and can sustain the discharge. The efficiency of the power coupling is few per cent and is sensitive to separation between dielectric and slow-wave structure.

Keywords. Surface plasma waves; slow-wave structures; plasma discharge; corrugated waveguide.

PACS Nos 52.40.Db; 52.50.Sw; 41.20.Jb; 42.25.Bs; 52.35.Hr

1. Introduction

Plasma-assisted deposition and etching are currently being used in industries as basic tools necessary for the mass production of various electronic devices. The next generation of microelectronics characterized with ~0.1 μm structures and giant-electronics with ~1 m^2 flat panels have pushed the development of high density ($>10^{11}$ cm^{-3}) large-area plasmas (>30 cm diameter) at low pressures ($<$ 10 mTorr) [1,2]. Two major techniques employed for plasma generation in processing applications are by employing electron beam or microwaves as they enable a high rate of deposition/etching even at low pressures [3–7]. The main advantage of microwave heating is the specificity of microwave energy absorption. In contrast to all other commonly used methods, microwaves allow volumetric heating of materials. Microwave energy transforms heat inside the material, which results in significant energy savings and reduction in process time. With all these advantages, the major drawback of microwave created plasmas is its inability to create large-volume homogenous plasmas because of small penetration depth. Here one could make use of the microwave power by coupling it to a surface plasma wave (SPW) which in turn can sustain discharge (a SPW is an electromagnetic wave that propagates at the boundary between two media with different conductivities, e.g. free space–dielectric interface and its amplitude peaks at the interface and drop off sharply away from it) [8–11]. This is achieved by keeping the dielectric in contact with a second medium that is conducting so that the field can couple its energy to the modes of the system. The plasma is produced as a result of the energy absorption of an electromagnetic wave propagating in a plasma–dielectric waveguide. Earlier studies on this line were limited to narrow cylindrical dielectric tubes, but the recent trend toward large-area plasma processing has driven the development of a planar surface wave plasma of diameter greater than 20 cm. The excitation of waves in multicomponent waveguide structures including structures that slow down the waves is most efficient in the eigenfrequency range. This is the reason for the interest in the spectra of waves in waveguides with slowing down structures [12–14]. In particular, slowing down structures are used to increase microwave power in generators based on plasma-filled waveguides. Various dielectric and semiconductor elements in metal waveguides increase the number of their natural modes and give rise to new effects accompanying wave propagation, e.g. excitation of SPW in these waveguides. Such large area surface wave plasma sources have been reported using a microwave launcher of large aperture formed on a waveguide, a dielectric line, and a slotted antenna with most of them operating at a frequency of 2.45 GHz. Al-Shamma'a *et al* have designed a 2.5 GHz waveguide-based microwave plasma jet at atmospheric pressure for material processing [15]. Bykov *et al* have given an elegant review of the physical aspects of high-temperature microwave processing of materials [16].

One of the methods for SPW excitation and sustained plasma discharge is by employing corrugated wall waveguide structure. Such type of structures have been able to sustain large-volume plasma exceeding 1000 cm^{-3} [16]. In this paper we report a theoretical formalism of SPW excitation and its coupling with slow wave. When a periodic slotted slow-wave structure separated by a thin dielectric slab is placed over the plasma surface, the SPW couples with the slow wave of the slow-wave–dielectric structure to give a slow surface plasma wave. This slow surface plasma wave can sustain a large volume plasma for material processing. In §2, we obtain the dispersion relation for the slow SPW. In §3, we study microwave power coupling to the slow SPW and in §4 we discuss our results.

2. Dispersion relation

Consider a free space–dielectric–plasma interface as shown in figure 1. Over the dielectric, at a height $x = b$, a slotted periodic slow-wave structure with height h and width d is placed. A microwave field $\vec{E} = \hat{x} A_0 \mathrm{e}^{-i(\omega t - k_z z)}$ is incident over the structure at $z = 0$. On applying Maxwell's equations, various field components in the above regions can be written as follows:

A. *Plasma*, $x < 0$

$$E_z = \sum_n A_{1n} \mathrm{e}^{\alpha_{1n} x} \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}, \tag{1a}$$

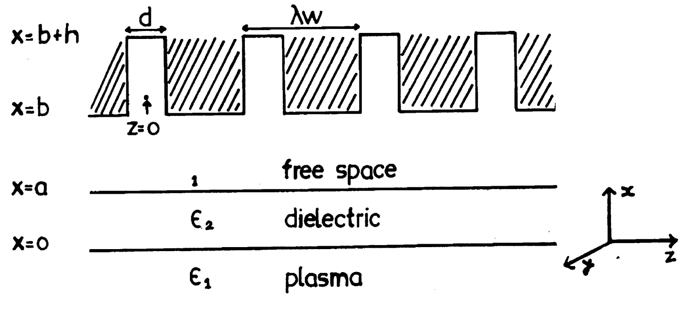


Figure 1. Geometry of the system.

$$E_x = -\sum_n A_{1n} \frac{i(k_z + k_n)}{\alpha_{1n}} \mathrm{e}^{\alpha_{1n} x} \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}. \tag{1b}$$

Here, A_{1n} is a constant, n is the number of slots, $k_n = nk_w$, $k_w = 2\pi/\lambda_w$, λ_w being the periodicity of slots, $\alpha_{1n} = \sqrt{(k_z + k_n)^2 - \omega^2 \varepsilon_1/c^2}$, $\varepsilon_1 = \sqrt{1 - \omega_p^2/\omega^2}$, $\omega_p^2 = 4\pi n_0 e^2/m$, n_0, e and m are electron density, charge, and mass, respectively.

B. *Dielectric*, $0 < x < a$

$$E_z = \sum_n (A_{2n} \mathrm{e}^{\alpha_{2n} x} + A'_{2n} \mathrm{e}^{-\alpha_{2n} x}) \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}, \tag{2a}$$

$$E_x = -\sum_n (A_{2n} \mathrm{e}^{\alpha_{2n} x} - A'_{2n} \mathrm{e}^{-\alpha_{2n} x}) \frac{i(k_z + k_n)}{\alpha_{2n}} \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}. \tag{2b}$$

Here, A$_{2n}$ and A'_{2n} are constants, $\alpha_{2n} = \sqrt{(k_z + k_n)^2 - \omega^2 \varepsilon_2/c^2}$ and ε_2 is the dielectric constant of the dielectric.

C. *Free space*, $a < x < b$

$$E_z = \sum_n (A_{3n} \mathrm{e}^{\alpha_{3n} x} + A'_{3n} \mathrm{e}^{-\alpha_{3n} x}) \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}, \tag{3a}$$

$$E_x = -\sum_n (A_{3n} \mathrm{e}^{\alpha_{3n} x} - A'_{3n} \mathrm{e}^{-\alpha_{3n} x}) \frac{i(k_z + k_n)}{\alpha_{3n}} \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}, \tag{3b}$$

$$H_y = \frac{\omega}{ic} \sum_n \frac{1}{\alpha_{3n}} \left(A_{3n} \mathrm{e}^{\alpha_{3n} x} - A'_{3n} \mathrm{e}^{-\alpha_{3n} x} \right) \mathrm{e}^{-i[\omega t - (k_z + k_n) z]}. \tag{3c}$$

Here A_{3n} and A'_{3n} are constants, $\alpha_{3n} = \sqrt{(k_z + k_n)^2 - \omega^2/c^2}$.

D. *Inside slots* $b < x < b + h$

$$E_z = A_4 \sin \frac{\omega}{c}(x - b - h) \mathrm{e}^{-i(\omega t - \theta_s)}, \tag{4a}$$

$$E_x = 0, \tag{4b}$$

$$H_y = iA_4 \cos \frac{\omega}{c}(x - b - h)\mathrm{e}^{-i(\omega t - \theta_s)}. \tag{4c}$$

Here A_4 is constant and $\theta_s = sk_z\lambda_w$ in the sth slot.

Demanding the continuity of E_z and εE_x at $x = 0$ and $x = a$ we obtain

$$A_{2n} + A'_{2n} = A_{1n}, \tag{5}$$

$$A_{2n} - A'_{2n} = \frac{\varepsilon_1}{\varepsilon_2}\frac{\alpha_{2n}}{\alpha_{1n}}A_{1n}, \tag{6}$$

$$A_{2n}\mathrm{e}^{\alpha_{2n}a} + A'_{2n}\mathrm{e}^{-\alpha_{2n}a} = A_{3n}\mathrm{e}^{\alpha_{3n}a} + A'_{3n}\mathrm{e}^{-\alpha_{3n}a}, \tag{7}$$

and

$$A_{2n}\mathrm{e}^{\alpha_{2n}a} - A'_{2n}\mathrm{e}^{-\alpha_{2n}a} = \frac{\alpha_{2n}}{\varepsilon_2\alpha_{3n}}\left(A_{3n}\mathrm{e}^{\alpha_{3n}a} - A'_{3n}\mathrm{e}^{-\alpha_{3n}a}\right). \tag{8}$$

Similarly, demanding the continuity of E_z at $x = b$, we obtain from eqs (3a) and (4b)

$$\sum_n \left(A_{3n}\mathrm{e}^{\alpha_{3n}b} + A'_{3n}\mathrm{e}^{-\alpha_{3n}b}\right)\mathrm{e}^{i(k_z+k_n)z} = F, \tag{9}$$

where $F = -A_4 \sin \frac{\omega h}{c}\mathrm{e}^{i\theta_s}$ inside the slot and $F = 0$ in between the slots at $x = b$. On multiplying eq. (9) by $\mathrm{e}^{-i(k_z+k_n)z}$ and integrating over z from $-\lambda_w/2$ to $\lambda_w/2$ we obtain

$$A_{3n}\mathrm{e}^{\alpha_{3n}b} + A'_{3n}\mathrm{e}^{-\alpha_{3n}b} = -A_4\frac{1}{\lambda_w}\sin\left(\frac{\omega h}{c}\frac{2}{k_z + k_n}\right)\sin\left(k_z + k_n\right)\frac{d}{2}. \tag{10}$$

We also demand at $x = b$, $\langle H_y\rangle_{\text{free space}} = H_y$ in the slot where $\langle\ \rangle$ denotes average over $-d/2$ to $d/2$ and obtain from eqs (3c) and (4c)

$$-i\frac{\omega}{c}\sum_n \frac{2}{\alpha_{3n}(k_z + k_n)}\left(A_{3n}\mathrm{e}^{\alpha_{3n}b} - A'_{3n}\mathrm{e}^{-\alpha_{3n}b}\right)\sin\left((k_z + k_n)\frac{d}{2}\right)$$
$$= iA_4\cos\left(\frac{\omega h}{c}\right). \tag{11}$$

Equations (5) and (6) on simplification gives,

$$A_{2n} = \frac{1 + \varepsilon_1\alpha_{2n}/\varepsilon_2\alpha_{1n}}{2}A_{1n}, \tag{12}$$

and

$$A'_{2n} = \frac{1 - \varepsilon_1\alpha_{2n}/\varepsilon_2\alpha_{1n}}{2}A_{1n}. \tag{13}$$

Using eqs (12) and (13) in eqs (7) and (8) and on simplification we get

$$\begin{aligned} A_{3n}\mathrm{e}^{\alpha_{3n}a} = \frac{A_{1n}}{2}\Bigg[&\left(1+\frac{\alpha_{3n}\varepsilon_1}{\alpha_{1n}}\right)\cosh(\alpha_{2n}a) \\ &+\left(\frac{\varepsilon_1\alpha_{2n}}{\varepsilon_2\alpha_{1n}}+\frac{\varepsilon_2\alpha_{3n}}{\alpha_{2n}}\right)\sinh(\alpha_{2n}a)\Bigg], \end{aligned} \tag{14}$$

and

$$\begin{aligned} A'_{3n}\mathrm{e}^{-\alpha_{3n}a} = \frac{A_{1n}}{2}\Bigg[&\left(1-\frac{\alpha_{3n}\varepsilon_1}{\alpha_{1n}}\right)\cosh(\alpha_{2n}a) \\ &+\left(\frac{\varepsilon_1\alpha_{2n}}{\varepsilon_2\alpha_{1n}}-\frac{\varepsilon_2\alpha_{3n}}{\alpha_{2n}}\right)\sinh(\alpha_{2n}a)\Bigg]. \end{aligned} \tag{15}$$

Equations (14) and (15) on further simplification gives

$$A'_{3n} = A_{3n}R_n\mathrm{e}^{2\alpha_{3n}a}, \tag{16}$$

where

$$R_n = \frac{(1-\alpha_{3n}\varepsilon_1/\alpha_{1n})\cosh(\alpha_{2n}a)+(\varepsilon_1\alpha_{2n}/\varepsilon_2\alpha_{1n}-\varepsilon_2\alpha_{3n}/\alpha_{2n})\sinh(\alpha_{2n}a)}{(1+\alpha_{3n}\varepsilon_1/\alpha_{1n})\cosh(\alpha_{2n}a)+(\varepsilon_1\alpha_{2n}/\varepsilon_2\alpha_{1n}+\varepsilon_2\alpha_{3n}/\alpha_{2n})\sinh(\alpha_{2n}a)}. \tag{17}$$

Using eq. (16) in (10) we get

$$\begin{aligned} A_{3n}\left(\mathrm{e}^{\alpha_{3n}b}+R_n\mathrm{e}^{\alpha_{3n}(2a-b)}\right) &= -\frac{2A_4}{(k_z+k_n)\lambda_w}\sin\left(\frac{\omega h}{2}\right) \\ &\quad\times\sin\left((k_z+k_n)\frac{d}{2}\right). \end{aligned} \tag{18}$$

Using eqs (16) and (18) in eq. (11) we obtain the dispersion relation

$$\sum_n \left(\frac{\sin\left((k_z+k_n)\frac{d}{2}\right)}{(k_z+k_n)\frac{d}{2}}\right)^2 \frac{\left(1-R_n\mathrm{e}^{2\alpha_{3n}(a-b)}\right)}{\left(1+R_n\mathrm{e}^{2\alpha_{3n}(a-b)}\right)}\frac{\omega}{\alpha_{3n}c} = \frac{\lambda_w}{d}\cot\left(\frac{\omega h}{2c}\right). \tag{19}$$

We have solved eq. (19) numerically and the dispersion relation (ck_z/ω_p vs. ω/ω_p) has been plotted in figures 2a–e for various values of normalized parameters, $\lambda'_w = \lambda_w\omega_p/c$, $d' = d\omega_p/c$, $a' = a\omega_p/c$, $a' = a\omega_p/c$, $h'_{ei} = h\omega_p/c$ and number periods n. The phase velocity of wave decreases with height, periodicity and number of slow-wave structures and by increasing the dielectric width and plasma density. However, it increases by increasing the dielectric width and plasma density. However, it increases with increase in the space between dielectric and periodic structures. The frequency of the SPW depends upon plasma frequency ω_p and the condition for the excitation of SPW is $\omega < \omega_p/\sqrt{(1+\varepsilon)}$. For a 2.45 GHz microwave source and plasma density $\sim 10^{11}$ cm^{-3}, the frequency range of the excited SPW is 1.5×10^9 rad/s to 10^{10} rad/s for the parameters mentioned in figures 2a–e.

Here it will be worthwhile to mention that the threshold for excitation of SPW depends upon the ionization potential I_p of the gas in the chamber and the threshold microwave power P_{th} is given by $P_{\text{th}} \geq m\omega^2 n\varepsilon_0 cI_p/e^2$ W/cm^2, where $n = \sqrt{\varepsilon} = \sqrt{1-\omega_p^2/\omega^2}$, and ε_0 is the free space permittivitty. However, once the discharge is sustained the electron–ion collision comes into play and the threshold power modifies to $P_{\text{th}} \geq m\omega^2 n\varepsilon_0 cI_p\delta/e^2$ where δ is the mean fraction of energy lost in the electron–ion collisions [8].

3. Power coupling

Let the incident microwave has a spot size $x = b_2 - b_1$ (see figure 3). At $z = 0$, the electric field of microwave can be expressed as

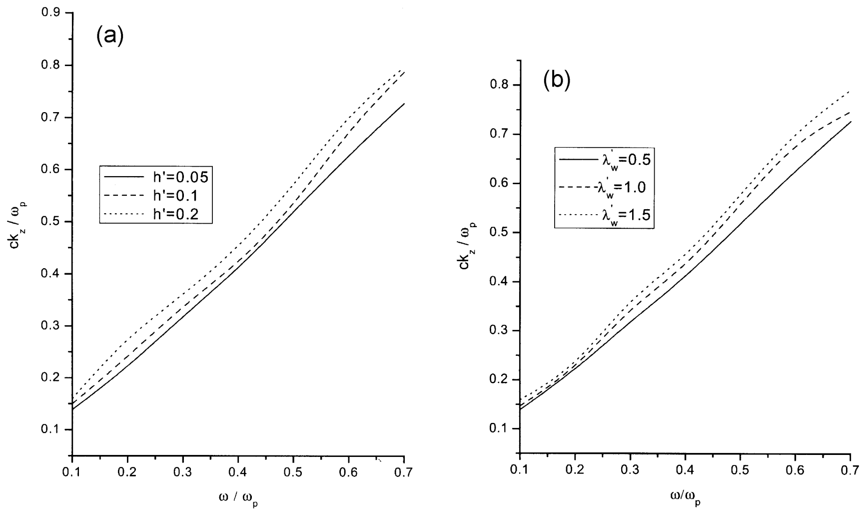
$$\begin{aligned} E_x &= A_0 \mathrm{e}^{-i\omega t} \quad \text{for} \quad b_1 < x < b_2, \\ &= 0, \qquad\qquad \text{outside.} \end{aligned} \tag{20}$$

From eqs (1a), (2b) and (3b), the x-component of the field is rewritten as

$$E_x = \sum_n a_n \psi_n, \tag{21}$$

where

$$a_n = \frac{\int_{-\infty}^{\infty} E_x \psi_n^* \mathrm{d}x}{\int_{-\infty}^{\infty} \psi_n \psi_n^* \mathrm{d}x} = \frac{A_0 \int_{b_1}^{b_2} \psi_n \mathrm{d}x}{\int_{-\infty}^{\infty} \psi_n \psi_n^* \mathrm{d}x}, \tag{22}$$



Figures 2a and b.

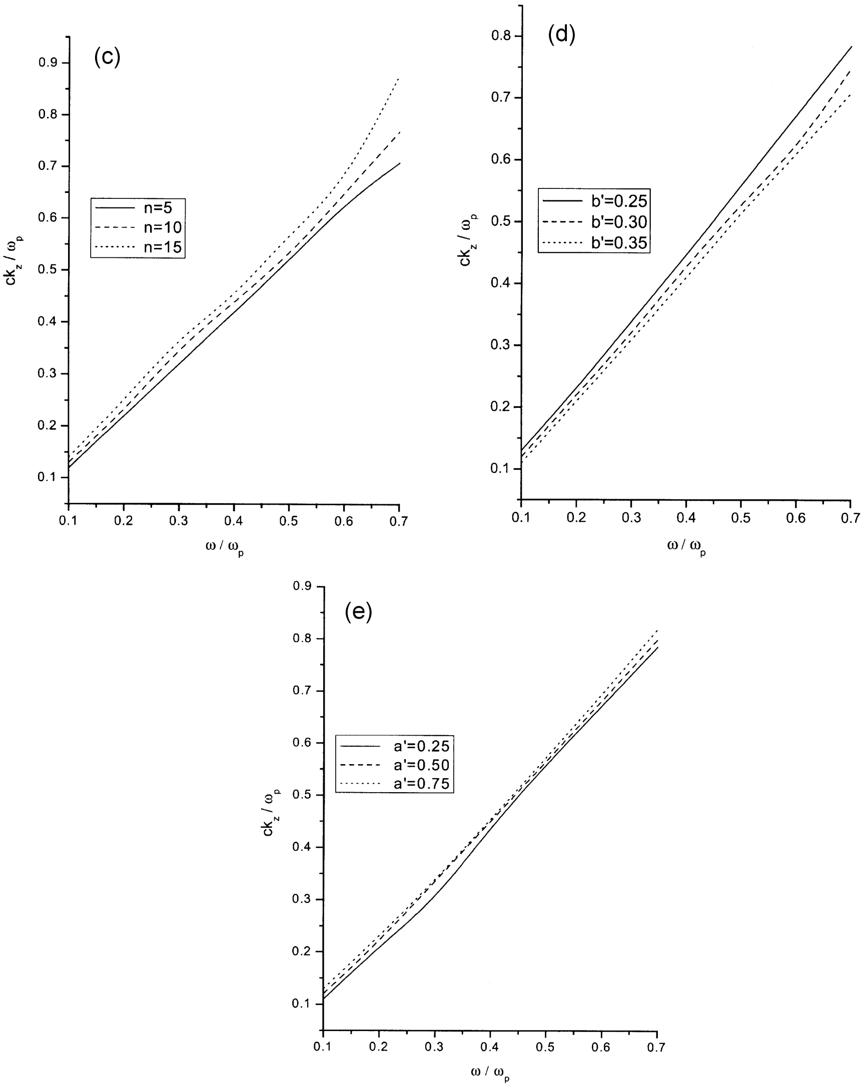


Figure 2. (**a**) Dispersion relation of the slow surface wave at various values of normalized height of periodic structures $h' = 0.05$, 0.1 and 0.2 for $n = 5$, $\lambda'_w = 1$, $a' = 0.25$, $b' = 0.26$, $d' = 0.25$. (**b**) Dispersion relation of the slow surface wave at various values of normalized wavelength (periodicity) of periodic structures $\lambda'_w = 0.5$, 1 and 1.5 for $h' = 0.05$, $n = 5$, $a' = 0.25$, $b' = 0.26$, $d' = 0.25$. (**c**) Dispersion relation of the slow surface wave at different number of periodic structures $n = 5$, 10 and 15 for $h' = 0.05$, $\lambda'_w = 1$, $a' = 0.25$, $b' = 0.26$, $d' = 0.25$. (**d**) Dispersion relation of the slow surface wave at various values of normalized spacing between periodic structures and dielectric $b' = 0.26$, 0.30 and 0.35 for $h' = 0.05$, $n = 5$, $\lambda'_w = 1$, $a' = 0.25$, $d' = 0.25$. (**e**) Dispersion relation of the slow surface wave at various values of normalized dielectric width $a' = 0.25$, 0.50 and 0.75 for $h' = 0.05$, $n = 5$, $\lambda'_w = 1$, $b' = a' + 0.01$, $d' = 0.25$.

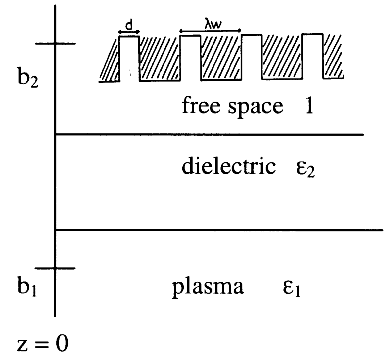


Figure 3. Geometry of power coupling.

and

$$
\begin{aligned}
\psi_n &= -\sum_n \frac{i(k_z+k_n)}{\alpha_{1n}} \mathrm{e}^{\alpha_{1n}x}, \quad \text{for } x<0 && \text{(23a)}\\
&= -\sum_n \left(A_{2n}\mathrm{e}^{\alpha_{2n}x} - A'_{2n}\mathrm{e}^{-\alpha_{2n}x}\right) \frac{i(k_z+k_n)}{\alpha_{2n}A_{1n}}, \quad \text{for } 0<x<a && \text{(23b)}\\
&= -\sum_n \left(A_{3n}\mathrm{e}^{\alpha_{3n}x} - A'_{3n}\mathrm{e}^{-\alpha_{3n}x}\right) \frac{i(k_z+k_n)}{\alpha_{3n}A_{1n}}, \quad \text{for } a<x<b. && \text{(23c)}
\end{aligned}
$$

On solving eq. (22) and using eqs (12)–(15) we obtain the efficiency of power coupling as

$$
\frac{a_n}{A_0} = \frac{-\sum_n (P_{1n}+P_{2n}+P_{3n})}{\sum_n (Q_{1n}+Q_{2n}+Q_{3n})} = \eta, \tag{24}
$$

where

$$
\begin{aligned}
P_{1n} &= \frac{i(k_z+k_n)^2}{\alpha_{1n}^2}\left(1-\mathrm{e}^{\alpha_{1n}b}\right),\\
P_{2n} &= \frac{i(k_z+k_n)^2}{\alpha_{2n}^2}\left\{\sinh(\alpha_{2n}a) + \frac{\varepsilon_1\alpha_{2n}}{\varepsilon_2\alpha_{1n}}\left(\cosh(\alpha_{2n}a)-1\right)\right\},\\
P_{3n} &= -\frac{2i(k_z+k_n)^2\sinh\left(\alpha_{3n}(a-b)/2\right)}{\alpha_{1n}\alpha_{2n}\alpha_{3n}^2\varepsilon_2}\\
&\quad \times[\sinh(\alpha_{2n}a)\{\sinh(\alpha_{3n}(a-b)/2)\alpha_{1n}\alpha_{3n}\varepsilon_2^2\\
&\quad -\cosh(\alpha_{3n}(a-b)/2)\alpha_{2n}^2\varepsilon_1\} - \cosh(\alpha_{2n}a)\alpha_{2n}\varepsilon_2\\
&\quad \times\{\cosh(\alpha_{3n}(a-b)/2)\alpha_{1n} - \sinh(\alpha_{3n}(a-b)/2)\alpha_{3n}\varepsilon_1\}],\\
Q_{1n} &= \frac{(k_z+k_n)^3}{2\alpha_{1n}^3},
\end{aligned}
$$

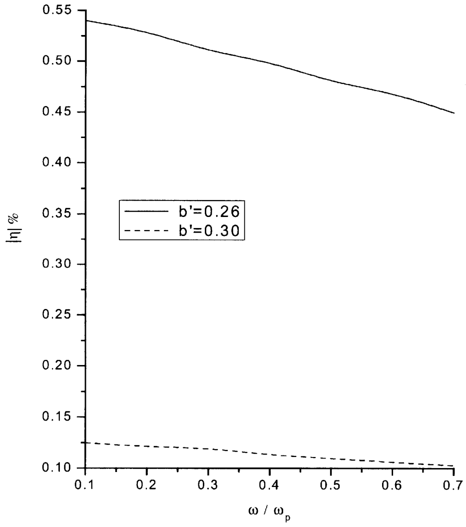


Figure 4. Variation of power coupling efficiency with normalized microwave frequency for $n = 5$, $a' = 0.25$, $b' = 0.26$ and 0.30, $\lambda'_w = 1$, $h' = 0.1$ and $d' = 0.25$.

$$
\begin{aligned}
Q_{2n} = {} & \frac{(k_z + k_n)^3}{2\alpha_{2n}^3}\left[-\frac{1}{2} + \frac{1}{2}\cosh(2\alpha_{2n}a) - \frac{\varepsilon_1^2\alpha_{2n}^2}{2\varepsilon_2^2\alpha_{1n}^2}\right. \\
& \left. + \frac{\cosh(2\alpha_{2n}a)\alpha_{2n}^2\varepsilon_1^2}{2\alpha_{1n}^2\varepsilon_2^2} + \frac{\sinh(2\alpha_{2n}a)\alpha_{2n}^2\varepsilon_1}{\alpha_{1n}^2\varepsilon_2^2}\right],
\end{aligned}
$$

$$
\begin{aligned}
Q_{3n} = {} & \frac{(k_n + k_z)^2 \mathrm{e}^{-2\alpha_{3n}a}}{8\alpha_{3n}^3} \\
& \times \left[\mathrm{e}^{4\alpha_{3n}a}(\mathrm{e}^{-2\alpha_{3n}b} - \mathrm{e}^{-2\alpha_{3n}a})\left\{\cosh(\alpha_{2n}a)\left(1 - \frac{\varepsilon_1\alpha_{3n}}{\alpha_{1n}}\right)\right.\right. \\
& \left. + \sinh(\alpha_{2n}a)\left(\frac{\varepsilon_1\alpha_{2n}}{\varepsilon_2\alpha_{1n}} - \frac{\varepsilon_2\alpha_{3n}}{\alpha_{2n}}\right)\right\}^2 \\
& + (\mathrm{e}^{2\alpha_{3n}b} - \mathrm{e}^{2\alpha_{3n}a})\left\{\cosh(\alpha_{2n}a)\left(1 + \frac{\varepsilon_1\alpha_{3n}}{\alpha_{1n}}\right)\right. \\
& \left.\left. + \sinh(\alpha_{2n}a)\left(\frac{\varepsilon_1\alpha_{2n}}{\varepsilon_2\alpha_{1n}} + \frac{\varepsilon_2\alpha_{3n}}{\alpha_{2n}}\right)\right\}^2\right].
\end{aligned}
$$

In figure 4 we have plotted eq. (24) of power coupling efficiency with normalized microwave frequency for $n = 5$, $a' = 0.25$, $b' = 0.26$ and 0.30, $\lambda'_w = 1$ and $d' = 0.25$. The efficiency of microwave coupling decreases sharply by increasing the spacing b between the periodic structure and the dielectric and it decreases gradually with decreasing plasma density.

4. Discussion

The plasma–dielectric–slow-wave structure can support two different waves. One is the plasma mode that originates from the plasma surface wave propagating along the interface between the plasma and the dielectric and the other is the guide mode that originally travels along the slow-wave structures. Propagation of the slow SPW is strongly affected by various parameters of slow-wave structures. The phase velocity of wave decreases with height, periodicity and number of slow-wave structures and by increasing the dielectric width and plasma density. However, it increases by increasing the dielectric width and plasma density. However, it increases with increase in the space between dielectric and periodic structures. Thus it is possible to tune the system over a large plasma density by varying any of the system parameters. Since the slow wave is the mode of the system, it couples efficiently with the plasma to sustain discharge. Thus the microwave energy can be transported to the plasma by exciting slow SPW, which in turn can sustain the discharge for material processing applications. The efficiency of microwave coupling decreases sharply by increasing the spacing b between the periodic structure and the dielectric. This is because of the fact that by increasing the spacing b, the phase velocity of excited slow SPW increases thereby reducing the coupling (see figure 2e). However, the variation of the coupling efficiency with plasma density is gradual and it decreases with decreasing plasma density again due to increase in phase velocity of the wave. For a better control over the microwave excited discharges one can apply a T-junction tuning system as proposed by Kudela *et al* [3]. The present study is also helpful in understanding transmission of high-power millimeter wave for electron cyclotron heating of fusion plasmas. It is also relevant to frequency selective mode reflectors as well as to high-power microwave generators employing slow-wave structures, viz. backward wave oscillator.

Acknowledgement

The authors are grateful to V K Tripathi, Physics Department, IIT, Delhi, India and C S Kou, Department of Physics, National Tsing Hua University, Hsinchu, Taiwan for valuable discussions. This work was supported by the University Grants Commission, New Delhi, India under Grant No. F-10-28/2001/SR-I.

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