Calculation of Long Surface Wave Produced Plasma (SWP) Cable

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Abstract:

Recently, the surface wave produced plasma (SWP)[1] has been paid attractive attention in the processing plasma, not only in the large area flat plasma source. We have developed a new SWP[2] using a long coaxial flexible antenna applying to produce various types of plasma. We can obtain characteristics of the surface wave in an axially symmetric chamber excited by the coaxial antenna using the finite element analysis.

Introduction:

As shown in Fig. 1, in the previous time, the SWP was produced in inner side when conductor is outer side, later the two dimensional techniques to produce SWP was developed and was used in VLSI design, in our novel technique, the SWP is produced outer side of conductor. We studied the characteristic of the SWP by using FEM and FDTD method.

Finite Element Formulations

We consider the geometry illustrated in Fig. 2 where coaxial antenna is connected to the chamber filled with an axially symmetric plasma VHF wave (298 MHz) is incident from the left through the coaxial antenna.

![Diagram of previous SWP, 2 dimensional SWP, and novel SWP](image)

Fig. 1 Various methods of Plasma Producing Techniques
This geometry is rotationally symmetric with respect to the axis of the antenna, thus, we can analyze the axisymmetric problem, which is substantially two-dimensional in the rz-plane as shown in Fig. 3.

The governing equation is written for the incident TM wave \((E_r, H_z, F_z)\) as,

\[
\frac{\partial}{\partial r} \left( \frac{1}{\varepsilon_r} \frac{\partial}{\partial r} (rH_\theta) \right) + \frac{\partial}{\partial z} \left( \frac{1}{\varepsilon_r} \frac{\partial H_\theta}{\partial z} \right) - k^2 H_\theta = 0 \quad (1)
\]

We solve the equation (1) using the finite element method. The solution domain is subdivided into triangular ring elements. Cross section of the cylindrical geometry of sample finite element subdivision is shown in elsewhere[3]. The Galerkin method is applied to (1) and the weighted residual integration for the weighting functions is set equal to zero and is described in the following.
\[ \int_{\Omega} \left[ \frac{\partial}{\partial \tau} \left( \frac{1}{\varepsilon_\tau} \frac{\partial}{\partial \tau} \left( rH_\theta \right) \right) + \frac{\partial}{\partial \tau} \left( \frac{1}{\varepsilon_\tau} \frac{\partial H_\theta}{\partial \tau} \right) - k^2 H_\theta \right] d\tau d\zeta = 0. \quad \ldots \quad (2) \]

Applying the Green's identity to the equation (2) and replacing \( w \) with a shape function \( N \), lead to the elemental equations for \( e \)-th element

\[ \int_{\Omega_e} \left[ N \left( N_1 \frac{\partial}{\partial \tau} \left( rH_\theta \right) + \frac{\partial N}{\partial \tau} \right) \right] d\tau d\zeta \]
\[ \int_{\Gamma_e} \left( N_1 \frac{\partial H_\theta}{\partial \tau} \right) d\tau d\zeta - j k \int_{\Gamma_e} \left( N_1 \varepsilon_\tau \right) d\tau = 0. \quad \ldots \quad (3) \]

where \( \Omega_e \) denotes the domain of the \( e \)-th element and \( \Gamma_e \) denotes our enclosing \( \Omega_e \). Assembling equations (3) for all elements yields the system of equations for \( \phi = rH_\theta \). Finally boundary conditions are imposed and especially on the fictitious open boundaries at the left side A and at the right side B are imposed the absorbing boundary conditions.

3. FD-TD Method

From the Maxwell's equations for TM wave, the equation of motion and the electron current density, the field elements \( E_z \) and \( H_\theta \) for three dimensional FD-TD method, which are shown in Fig. 4, are given numerically by,

![Fig. 4 Spatial Cell (i, j) of FD-TD Method](image-url)
\[
E_{t}^{n+1/2}(i+1/2, j) = E_{t}^{n-1/2}(i+1/2, j) + \frac{\Delta t}{\varepsilon \cdot \Delta z} (H_{r}^{n}(i-1/2, j+1/2) - H_{r}^{n}(i+1/2, j+1/2)) - c\Delta t \cdot Z_{0}J_{r}^{n}(i+1/2, j)
\]

\[
E_{z}^{n+1/2}(i+1/2, j) = E_{z}^{n-1/2}(i+1/2, j)
\]
Fig. 5 Variation of Electron Density with Distance n, with $\beta=0.0137$

Fig. 6 Amplitude of $H_z$ within the chamber (FEM Method) with $\alpha=0$ and $\beta=0.0137$

Fig. 7 Amplitudes of $H_z$ (FDTD—, FEM—- - -) on the surface of the coaxial antenna (1) $\nu/\omega=0.1$, (2) 0.25, (3) 0.5, (4) 1.0 and $\alpha=0$ and $\beta=0.023$
Numerical Results and Conclusions

Employed model is for \( r_0=0.15[\text{cm}] \), \( r_1=0.5[\text{cm}] \), \( R=30[\text{cm}] \), and \( L=500[\text{cm}] \). The calculations are made for the electron density profile \( n_e \) as shown in fig (5), that \( n_e \) decreases exponentially with increasing \( z \) according to equation (13) while it remains constant for \( r \) according to equation (12) with keeping \( \alpha=0 \). An example for the case that is \( n_e=10^{12}[\text{cm}^{-3}] \) at \( z=0 \) [cm] and \( n_e=10^9[\text{cm}^{-3}] \) at \( z=500[\text{cm}] \) is illustrated in Fig 6 Details of this figures are shown in elsewhere[3]. The result is that the surface wave excited on the antenna cannot propagate into the plasma media where the plasma frequency is nearly less than twice the incident VHF wave frequency.

\[
 n_e = n_{e0} \times \exp (-\alpha r) \quad \quad \quad \quad \quad \quad \quad (12)
\]

\[
 n_e = n_{e0} \times \exp (-\beta z) \quad \quad \quad \quad \quad \quad \quad (13)
\]

In equation (12) and (13), the \( n_e \) , \( n_{e0} \) , \( n_{e0} \), \( \alpha \), and \( \beta \) are the electron densities at radial distance \( r \) at axial distance \( z \) at a distance \( r=0 \) cm, \( z=0 \) cm, radialy and axially electron density decaying constants, respectively.

We simulate the surface waves, which sustain cylindrically stratified plasma over the cable by means of Finite Difference-Time Domain method from equation (4) to (11). As shown in Fig 7 the field profile of \( H_y \) for FD-TD method, shown by solid lines, nearly equals to that for FEM method, shown by dotted lines. We can design a long SWP cable under these results. This long SWP will be used in VLSI designing.

Acknowledgement

This work was supported partly by grants from The Industrial Consortium of NEDO, and from Establishment Project of the Ministry of Education, Science, Sports and Culture of Japan.

References