COMBLINE ANTENNAS
FOR LAUNCHING TRAVELING FAST WAVES

C.P. Moeller, R.W. Gould,* D.A. Phelps, and R.I. Pinsker
General Atomics, San Diego, CA 92186-9784

ABSTRACT

The combline structure shows promise for launching traveling fast magnetosonic waves with adjustable $n_\parallel$ ($3 \leqslant n_\parallel \leqslant 6$) for current drive.[1] In this paper, the dispersion and damping properties of the combline antenna with and without a Faraday shield are given. The addition of a Faraday shield which eliminates the electrostatic coupling between current straps as well as between the straps and plasma offers the advantage of eliminating the need for the lumped capacitors which are otherwise required with this structure. The results of vacuum dispersion and damping measurements on a low power model antenna are also given.

INTRODUCTION

For current drive, it is necessary to launch a unidirectional wave, and desirable to vary the launched $n_\parallel$ in the range 3 to 6 during a discharge while presenting a matched load to the generator, even as the plasma position and edge density vary. These additional requirements are much more easily achieved by a radiating slow wave structure, fed at one end, than by the array of individually fed current straps presently used for launching fast waves. Such a structure is inherently a traveling wave device, in which the mutual coupling between radiating elements is part of the wave propagation, in contrast to individually fed radiating elements, for which the mutual coupling leads to unequal loading of the elements. A single point feed also eliminates the need for most of the external matching networks the individually fed current straps require. The input will appear matched to the external transmission line if the structure is long enough to radiate all of the incident power, if the output is terminated in a matched load, or if the structure is made part of a resonant ring. With a matched input, for the same total power, the voltage at the vacuum feedthrough may be lower than that at the feedthroughs of the individually fed straps with their high VSWRs.

A slow wave structure which has elements closely resembling the current straps of present fast wave antennas is the combline,[2] which is shown schematically in Fig. 1 configured as an antenna. Except for being open at the front, this structure is identical to commercially available bandpass combline filters. As with any bandpass filter, as the frequency varies within the passband, the phase shift from element to element ranges from 0 radians at the lower cutoff to π radians at the upper cutoff, although as will be seen, the range from $\pi/4$ to $\pi/2$ is the most desirable with regard to ohmic loss and radiated wavenumber spectral purity. The two disadvantages of the combline antenna as shown in Fig. 1 are the lack of a Faraday shield, and the lumped capacitance which is required at the end of each current strap. Although the required capacitance is small, the required area is inconveniently large. Both these drawbacks can be overcome by configuring a Faraday shield as shown in Fig. 2, so as to eliminate capacitive coupling between current straps, as will be discussed in the next section.

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*Permanent Address: California Institute of Technology, Pasadena, CA 91125.

VACUUM DISPERSION PROPERTIES

The vacuum properties will be analyzed with the plasma replaced by a conducting wall, with the surface impedance of the plasma treated as a perturbation on the vacuum solution, in a extension of an approach used by Golant.[3] We can regard the array of current straps and the conducting walls as a section of multi-conductor transmission line, which is governed by the equations:

$$\frac{\partial V_r}{\partial y} = - i\omega \sum_s L_{rs} I_s \quad , \tag{1}$$

and

$$\frac{\partial I_r}{\partial y} = - i\omega \sum_s C_{rs} V_s \quad , \tag{2a}$$

where y is the coordinate along a conductor, $V_r(y)$ and $I_r(y)$ are the voltage and current on the r^{th} conductor at y, and L_{rs} and C_{rs} are the mutual inductance and capacitance per unit length, respectively, between the r^{th} and s^{th} conductors. With an ideal Faraday shield, which does not affect inductances but completely shields each bar electrostatically, Eq. (2a) is replaced by

$$\frac{\partial I_r}{\partial y} = - i\omega C_0 V_r \quad , \tag{2b}$$

where C_0 is the capacitance per unit length of each bar to its shield. With all the conductors grounded at $y = 0$, and assuming an infinite array of identical elements, we can let $V_r = V^0 \sin(\beta y)\exp(-ir\theta)$ and $I_r = I^0 \cos(\beta y)\exp(-ir\theta)$, where θ is the phase shift from element to element to be determined and β is the propagation constant along y. From (1) and (2a), respectively, we then obtain $V^0/I^0 = -i(\omega/\beta)\sum_s L_{0s}\exp(-is\theta) \equiv -i(\omega/\beta)L(\theta)$ and $I^0/V^0 = i(\omega/\beta)\sum_s C_{0s}\exp(-is\theta) \equiv i(\omega/\beta)C(\theta)$ where the $r = 0$ element is typical in the infinite array. With a shield the second equation is replaced by $I^0/V^0 = i(\omega/\beta)C_0$. Without the shield, $\beta/\omega = [L(\theta)C(\theta)]^{1/2} = 1/c$ for a TEM wave. With the shield, $\beta/\omega = [L(\theta)C_0]^{1/2}$. The dispersion relations are determined by the boundary conditions at $y = \ell$: $I_r/V_r = i\omega C_e$, C_e the lumped capacitance, without a shield and $I_r = 0$ and $\beta\ell = \pi/2$ with a shield. The corresponding dispersion relations are respectively

$$L(\theta)C_e = 1/[c\omega \tan(\omega\ell/c)] \quad , \tag{3a}$$

and

$$L(\theta)C_0 = 1/(2\ell\omega/\pi)^2 \quad . \tag{3b}$$

It is apparent that if $C_e = 0$ in (3a), the only solution is $\omega\ell/c = \pi/2$, giving zero pass band width and zero group velocity. With an electrostatic shield, corresponding to (3b), the lumped capacitance is unnecessary.

The total electromagnetic field energy in a unit cell without a shield is $W_{cell} = (1/4)V_p^2\{\ell/[c^2L(\theta)\sin^2(k_0\ell)] + C_e\}$, while with the shield it is $W_{cell} = (1/8)V_p^2\ell\{C_0 + (\pi/2)^2/[\omega^2\ell^2L(\theta)]\}$, where V_p is the peak voltage at the end of the strap. The power flow along the structure is then just $P_0 = W_{cell}d\omega/d\theta$.

We have solved for $C(\theta)$ using a variational technique for the geometry shown in Fig. 1. $L(\theta)$ is then obtained from $L(\theta) = 1/[C(\theta)c^2]$. With an ideal Faraday shield, $L(\theta)$ is presumed not to change, while we can calculate C_0 approximately using the same variational technique. An example of the dispersion properties is shown in Fig. 3, where, referring to Fig. 1, w = 5 cm, t = 2.5 cm, s = 5.4 cm, ℓ = 31.25 cm, and d_2 = 15 cm to a conducting front wall. For case A, d_1 = 5 cm, ℓ = 31.25 cm, and

and $C_e = 16$ pF; for case B, $d_1 = 2.5$ cm and $C_e = 20$ pF; case C is similar to A except $C_e = 0$, $\ell = 40$ cm, and there is a Faraday shield for which $C_0 = 96$ pF/m. Corresponding values of $V_p/(P_0)^{1/2}$ at the passband center, P_0 the input power, are $28\,V/W^{1/2}$ for case A, $32\,V/W^{1/2}$ for case B, and $25\,V/W^{1/2}$ for case C.

Regarding the spatial spectrum, the k_z values of the fields in the structure must satisfy $k_z = (\theta/p) + (2\pi N/p)$, where p is the period and N is an integer. The most troublesome harmonic has $N = -1$. By making p small, $k_{z(-1)}/k_{z(0)}$ can be made so large that the evanescent region can filter out the harmonic. In our example, $3 \leqslant |k_{z(-1)}/k_{z(0)}| \leqslant 7$.

PLASMA DAMPING

We have evaluated the plasma damping by determining Imn_z. n_z can be written in a Taylor series as

$$n_z\left(\rho_p\right) = n_{z0} + \left.\frac{dn_z}{d\rho}\right|_{\substack{\rho=\rho_r \\ u=u_r}} \left(\rho_p - \rho_r\right) + \dots \quad , \tag{4}$$

where n_{z0} is the vacuum n_z evaluated above with a conducting wall at u_0, ρ_r is the surface impedance at u_r with this wall present, while ρ_p is the surface impedance at u_r with a plasma replacing this wall (see Fig. 4). The ρ's are normalized to 377 ohm, and $u = k_0 x$.

The derivative in (4), $dn_z/d\rho$, can be evaluated from dn_{z0}/du_0, the change in n_{z0} due to the movement of the front conducting wall, which we evaluated numerically. The position u_0 of the wall can be chosen so that Re$\rho_p \approx \rho_r$, minimizing the importance of higher terms of the series. Assuming a 5 cm vacuum region($u_r/k_0 = 5$ cm), which is large in view of the radiated k_z, the distance along the structure for power to be reduced by $1/e$ is shown in Fig. 5 for two idealized DIII–D plasma profiles as a function of n_z. For purpose of comparison, the effective series resistance at the bottom of the strap necessary to reduce the power in the structure by $1/e$ in a meter is ≈ 0.57 ohm for case A and ≈ 0.24 ohm for case B. Even with this small loading resistance, the incident power is efficiently radiated, demonstrating the advantages of a slow wave structure. The predicted vacuum ohmic damping is in comparison only ≈1%/m for case A and 2%/m for case B.

Preliminary damping measurements using resistive films on a low power model have given the result that the measured damping is somewhat stronger than that calculated by the above model, so the curves of Fig. 5 are probably rather conservative.

CONCLUSIONS

We have described a periodic structure for efficiently launching traveling fast waves of high n_z. The n_z can be varied over a wide range with a moderate frequency change. The shielded version of this structure requires no loading capacitors and has lower peak voltages than the corresponding unshielded structure.

REFERENCES

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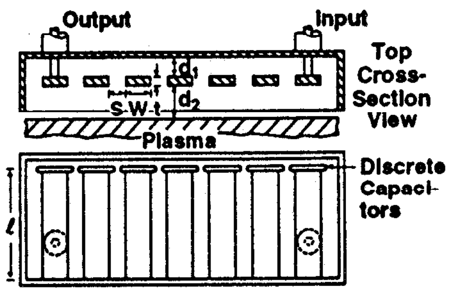

FIG. 1. Schematic of unshielded combline antenna.

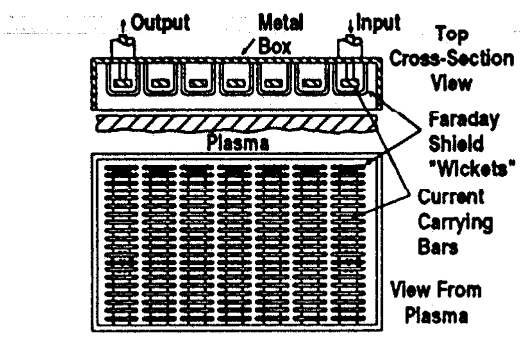

FIG. 2. Schematic of shielded combline antenna.

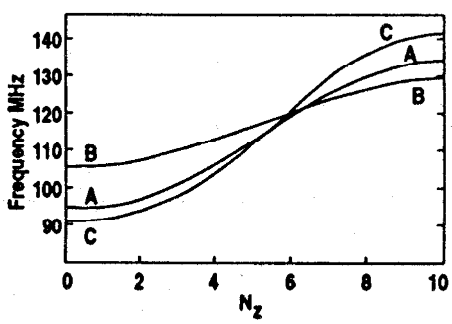

FIG. 3. Vacuum dispersion of the unshielded (cases A and B) and shielded (case C) combline antennas. A has 5 cm backplane spacing, compared to 2.5 cm for B. C is similar to A except for the shield. Other dimensions are given in the text.

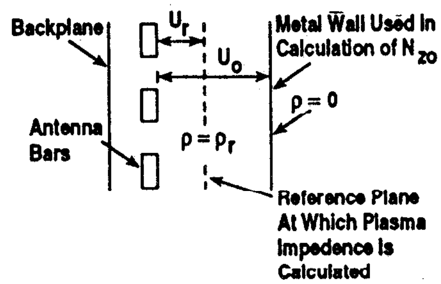

FIG. 4. Geometry of the loading calculation.

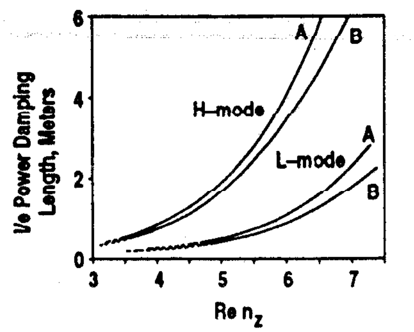

FIG. 5. Damping length for two idealized DIII–D plasma profiles for cases A and B.