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ICRF WAVE COUPLING AND OPTIMIZATION OF A DIELECTRIC-FILLED WAVEGUIDE LAUNCHER*

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ABSTRACT

A shorted-probe coupling scheme for a dielectric-filled, high power waveguide launcher for plasma heating has been constructed, modeled and analyzed. Measured reflection coefficients show good agreement with the model, especially in the optimum tuned region. The attenuation of the deionized water as the dielectric filler for the waveguide is examined as well.

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I. Introduction

To launch ICRF (Ion Cyclotron Range of Frequency) waves to a tokamak fusion reactor containing plasmas, a compact, dielectric-filled rectangular waveguide launcher has been designed. This is a two-port coupling device operated in ICRF range (60M-1GHz) and at high power transmission levels up to 5MW. To incorporate high power, low operating frequencies and compactness in size, a dielectric material with a very high ε_r must be placed inside the waveguide. This high ε_r (>50) significantly affects the tuning characteristics of the waveguide launcher coupled to the plasma.

In this work, we investigate the input impedance of a coaxial feed-shorted probe antenna in the dielectric-filled waveguide, and its input reflection coefficient. The Q value measurement and the attenuation coefficient of deionized water, which we used as the high-ε_r dielectric filler of the waveguide, are discussed. The experimental data of the coupling and tuning effects are also presented and compared with the model we derived.

II. Input Impedance and Reflection Coefficients

Collin [1] has examined the coupling scheme using an open-ended probe, as shown in Fig. 1a, and a probe current distribution as follows

$$\vec{J}_o(y') = \hat{a}_y J_o \sin k_{o\varepsilon} (d - y'), \quad o \leq y' \leq d \quad (1)$$

The input impedance of this open-ended probe given by Collin will result in an input reflection coefficient $|S_{11}|$ as shown in Fig. 2 for a given high ε_r of 78. Figure 2 shows that, as ε_r becomes very high, the open-ended probe fails to efficiently couple RF waves into the dielectric-filled waveguide for all possible tuning ranges of the sliding-short.

Therefore, a shorted probe was considered (Fig. 1b). The shorted probe has a different surface current distribution

$$\vec{J}s(y') = \hat{a}_y \cos k_{o\varepsilon} (d - y'), \quad o \leq y' \leq b \quad (2)$$

This driving current turns out to give an input impedance $Z_{in} = R_{in} + jX_{in}$

$$R_{in} = \frac{2\eta_\varepsilon \tan^2(k_{o\varepsilon} d)}{ab\beta_{10} k_{o\varepsilon}} \sin^2 (\beta_{10} \ell s) \quad (3)$$

$$X_{in} = \frac{\eta_\varepsilon \tan^2 (k_{o\varepsilon} d)}{2\pi b\, k_{o\varepsilon}} \left[\left\{\frac{2\pi}{a\beta_{10}}\right\} \sin (2\beta_{10} \ell s) + \ell n \left\{\frac{2a}{\pi r}\right\} + \frac{0.0518\, k_{o\varepsilon}^2 a^2}{\pi^2} - 2\left(1 - \frac{2r}{a}\right) - 2 k_{o\varepsilon}^2 \sum_{n=1}^{\infty} \frac{K_o(k_n r)}{k_n^2} \right] \quad (4)$$

where

- a,b = waveguide width and height;
- r,d = probe radius and depth (d = b for shorted probe);
- ℓs = tuning distance between the probe and the sliding-short;
- η_ε = $\eta_o/\sqrt{\varepsilon_r}$ = intrinsic impedance of the dielectric;
- β_{10} = $[k_{o\varepsilon}^2 - (\pi/a)^2]^{1/2}$ = TE_{10} mode propagation constant;
- k_n = $[(n\pi/b)^2 - k_{o\varepsilon}^2]^{1/2}$; and
- $K_o(k_n r)$ = modified zero-order Bessel function of second kind.

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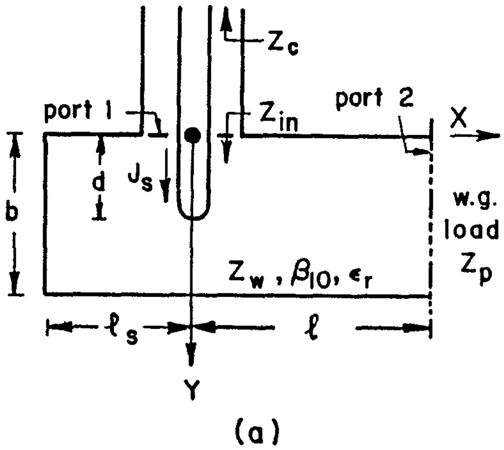

Fig. 1 Coaxial feeds for the waveguide; a) open-ended probe; b) shorted probe.

Using this impedance, we can obtain the input reflection coefficient with the waveguide matched at the output port

$$S_{11} = \frac{Z_{in} - R_o}{Z_{in} + R_o} \tag{5}$$

where R_o is the characteristic impedance of the coax feed. If the output port is instead loaded by the plasma impedance, the input reflection coefficient can be shown to have the form

$$S_{11}' = \frac{S_{11} + \Gamma'}{1 + S_{11}^{*}\Gamma'}, \tag{6}$$

where $\Gamma' = \Gamma e^{j2\phi_{12}}$, Γ is the reflection from the load and ϕ_{12} is the phase angle of S_{12}. $|S_{11}|$ and $|S_{11}'|$ have been simulated as functions of various waveguide parameters [2].

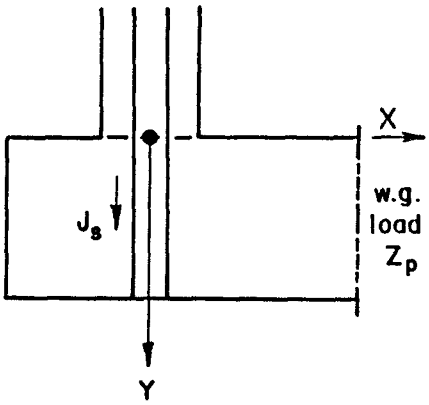

Fig. 2 Input reflection coefficient vs. d for open-ended probe and matched waveguide; ε_r = 78, f = 85 MHz, a = 24.8 cm, b = 12.4 cm, R_0 = 50 Ω, r = 0.24 cm.

III. Measurements

We used deionized water (ε_r = 78 in our frequency range) as the dielectric filler of the waveguide. To ensure that it has relatively low loss, we carried out the Q value measurement of the deionized water by a resonance cavity method using both loop and probe antenna couplings. Five resonant modes were tested with an averaged Q value being 185 at 100 MHz. This Q value gives an attenuation coefficient of 0.13 db/ft, which coincides with the data of Jackson [3]. Such a level of attenuation by the deionized water is considered acceptable for low power or high power cooled applications since the waveguide launcher would not be longer than five feet.

The lack of commercial matched loads for our 24 cm × 12 cm rectangular waveguide led us to construct a tapered matched load using the VF-60 absorbers of Emerson & Cuming. The matched load has a size (length × height × thickness) of 68.5 cm × 12.4 cm × 1.3 cm. We applied the time-domain gating functions of the HP 8510 Automatic Network Analyzer (ANA) to investigate the absorption by the matched load. Figure 3 shows the time-domain response of $|S_{11}|$ of the waveguide launcher before and after the matched load is inserted, respectively. Isolating the response due to only the matched load and transforming it into frequency domain by use of the inverse Fourier transform of ANA, we determined that the return loss of the matched load was more than 20 dB. This was adequate for us to match the output port of the dielectric-filled waveguide launcher for a tuning measurement.

Experiments to verify our model for the shorted probe coupling to the dielectric-filled waveguide launcher are illustrated in Fig. 4. The level of the dielectric filler is at the interface between the 50-ohm coax and the waveguide. We tuned the sliding-short distance ℓs and measured $|S_{11}|$ at the input port over 0.5 M-1.2 GHz (ε_r = 1) and 60 M-130 MHz (ε_r = 78) for various coupling probe radii. Figure 5 shows the comparison between the measurements and our model for given parameters. In Fig. 5, the two curves have a very close agreement, in particular in the optimum tuning region where the power coupling efficiency can be as high as 90%. A small tuning offset has been included. We also found that $|S_{11}|$ is not very sensitive to the change in the probe radius when the probe radius is sufficiently large ($\gtrsim$ 1 cm).

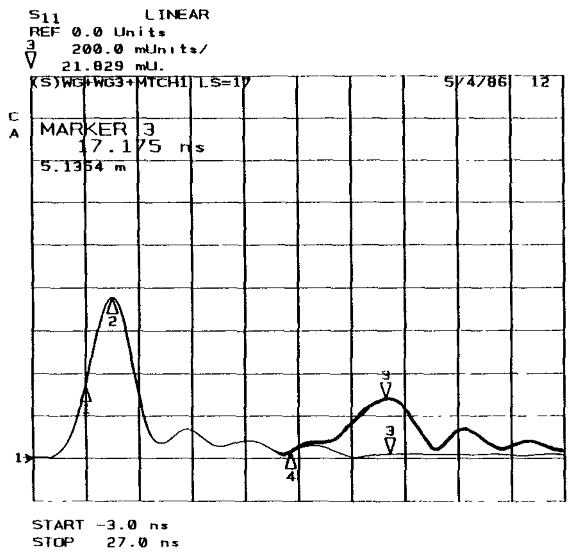

Fig. 3 Time-domain response of $|S_{11}|$ with the waveguide output port shorted (upper) and matched (lower), respectively.

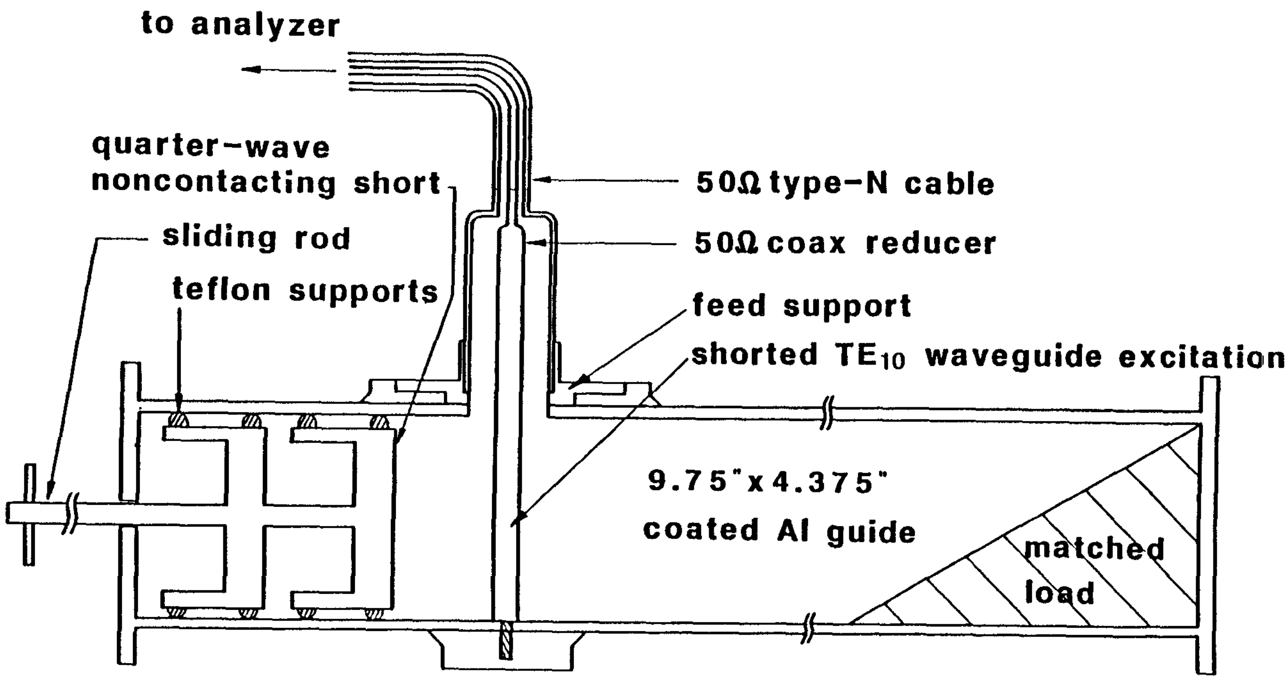

Fig. 4 Waveguide Launcher Structure (side view)

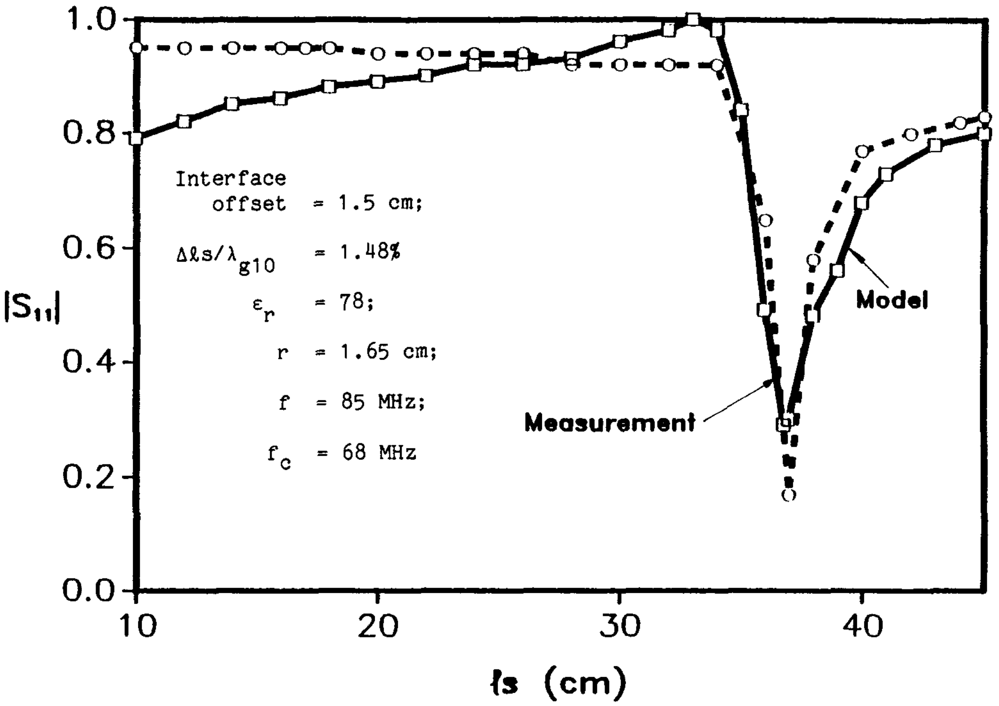

Fig. 5 Field Reflection Versus Sliding-Short Distance for a Matched Waveguide

IV. Conclusions

A shorted-probe coupling scheme for a dielectric-filled, high power waveguide launcher has been analyzed and laboratory measurements have been made. The input reflection coefficient has been measured and compared with our model. We obtained good agreement between the model and measurements, especially in the optimum tuned region. The loss test of the deionized water as the dielectric filler for the waveguide has an attenuation of 0.13 db/ft. The large matched load provides a return loss of more than 20 dB in RF frequencies.

References

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