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DESIGN OF TM_{0n}-MODE COUPLERS FOR DIAGNOSTICS OF A VIRCATOR

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Abstract—The waveguide and the coaxial-probe type wideband high power TM_{0n}-mode couplers ($n = 1, 2$) were designed and qualified with respect to the coupling factor using the wheel-type mode launchers. The mode launchers and the mode couplers were simulated and experimentally tested, the former for the VSWR and the latter for the coupling factor. The coupler chamber has been used in single-shot experiments, the values of the measured frequencies of coupled output of a typical vircator agreed with those predicted values by particle-in-cell code simulation using MAFIA.

1. INTRODUCTION

VIRTUAL cathode oscillator (Vircator) is a widely preferred high power microwave source, as it is simple in construction, requiring no external magnetic field for its operation. The electrons generated by a relativistic electron beam source are thrown through an anode foil or aperture into a drift space of a waveguide. A virtual cathode forms in the device when the beam current exceeds the space-charge limiting current that depends on the ratio of the beam to resonator wall radius. Microwave is generated due to bremsstrahlung of electrons as they oscillate between the actual and the virtual cathode [1].

The device generates a wide range of frequencies attributable to two different mechanisms of space-charge fluctuation arising from (i) the oscillation of electrons between the actual and virtual cathodes and (ii) the oscillation of the virtual cathode itself, in which the potential oscillates because of inherent instability of electron cloud in space and time [1]. These oscillations produce microwaves at wide frequency band

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in TM_{0n}-modes, typically for the vircator configuration of axial-output extraction. The frequency of the modes coupled to the cylindrical waveguide depends on the virtual cathode oscillation frequency (f_{oc}) and the electron reflection frequency (f_r). The oscillation frequency of the virtual cathode is related to the beam plasma frequency f_p, and generally lies in the frequency range of $f_p \leq f_{oc} \leq 2.5 f_p$ [2].

Thus, it becomes important to probe into the device output for the frequencies generated. For this purpose, the E-dot and the B-dot probes as well as the loop couplers are in vogue for the TE_{11} and the TM_{01} modes, respectively. In addition, a study on the radiated energy through the output window of the vircator is also a means for characterizing the device [3, 4]. However, the probe and the loop couplers often distort the field pattern. Moreover, this type of couplers has the limitation of handling high power levels generated by vircators. This calls for the development of high power, pure-mode wideband couplers for the fundamental as well as higher order modes with a view to characterizing high power vircators. The analysis and design of broad band directional coupler was reported by Tomita, M. and Y. Karasawa for a rectangular dielectric waveguide [7] and for a ultra broad band directional coupler was reported by M. Nedil and T. A. Denidni [8]. In the present paper, a design is developed for two such couplers, namely, (i) the wave guide coupler that makes use of an elliptical aperture and (ii) the tapered co-axial probe coupler (Fig. 1) by numerical simulation using HFSS.

Further, the study has also encompassed the design of wideband mode launchers, capable of exciting pure modes in the waveguide, which are required to qualify these couplers (Section 2). The mode launchers designed in this paper is of the wheel type that was proposed elsewhere for a corrugated slow-wave structure to excite the pure axis-symmetric TM_{0n} modes [5].

Due attention has been given to wideband performance of the

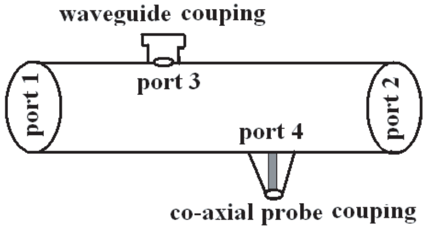

Figure 1. Schematic of waveguide aperture and tapered co-axial coupler.

mode launcher keeping in view the requirement for probing into wide range of frequencies generated in the vircator. The analysis of the mode launcher is developed following the equivalent circuit approach (Section 2). A particle-in-cell simulation has been carried for a typical vircator configuration using the 3D electromagnetic simulation tool MAFIA (solving Maxwell equation by Finite Integration Algorithm) [6] for the identification of the modes and frequencies generated in the vircator (Section 3). The VSWR of the mode launcher for the TM_{01} and TM_{02} modes obtained by analysis is validated against the commercial tool HFSS (high frequency structure simulator) as well as against experiment (Section 4). Further, the mode couplers qualified by the mode launchers are used in a practical measurement set-up to obtain experimental values of excited frequencies of a vircator for comparison with those obtained analytically as well as by MAFIA simulation (Section 4).

2. ANALYSIS

Both the waveguide coupler with an elliptical aperture and the tapered coaxial-probe coupler have been built in the same unit provided with the option that at a time one of them could be used, while terminating the other in a matched load (Fig. 1). The waveguide coupler has yielded a coupling factor of -48 dB. In this type of coupler, an S-band waveguide (WR284) is coupled to a cylindrical waveguide through an elliptical aperture excited in the dominant TE_{10}-mode such that the axial electric field of the rectangular waveguide couples the desired TM_{01}-mode in the cylindrical waveguide. The coaxial-probe coupler providing a coupling factor of -30 dB has been designed with a tapered cross-section outer conductor of the probe to match with a 50-Ohm coaxial output line (Fig. 1).

The couplers have been designed with the help of HFSS. For this purpose, the geometry (Fig. 1) is modeled and assigned waveguide boundary condition at the two ends of the cylindrical waveguide with all possible modes; those can exist within the frequency band. The port 3 is assigned at the S-band waveguide end and port 4 is assigned at the co-axial end as shown in Fig. 1. The return loss at the exciting port and the coupling factor of the S-band waveguide aperture coupler and the co-axial couplers are absorbed. To qualify the coupler experimentally, TM_{01} and TM_{02}-mode launchers are designed and fabricated and subsequently also tested by measurements.

The schematic diagram of TM_{01}-mode launcher is shown in Fig. 2(a). The modified structure for TM_{02}-mode launcher is shown in Fig. 2(b). The equivalent circuit representation of the mode launcher

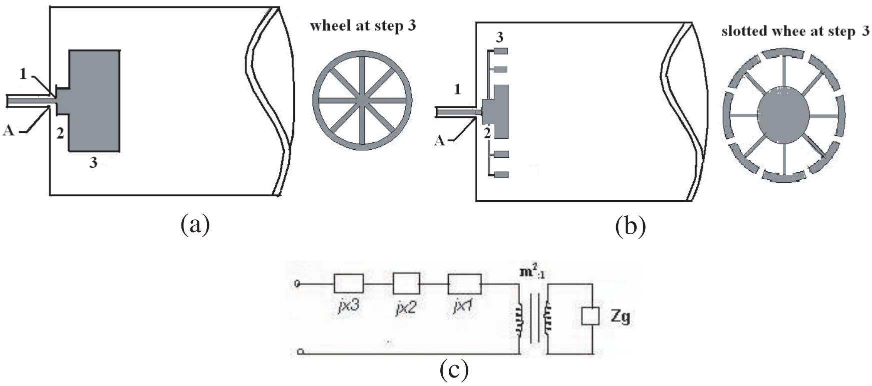

Figure 2. Schematic diagrams of (a) TM_{01}-mode launcher, (b) TM_{02}-mode launcher (c) its equivalent circuit representation.

having three steps impedance transformer is shown in Fig. 2(c).

The impedance matching from input (50 Ω coaxial) impedance to the waveguide impedance is carried out by a Chebyshev three-step impedance transformer (the three steps are numbered 1, 2, 3 in Figs. 2(a) and 2(b)) [9]. The parameters of the equivalent circuit can be determined by

$$jX_n = j\omega L_n, \tag{1}$$

here, $L_n = Z_{0n}/V_{pn}$ and $Z_{0n} = (L_n/C_n)^{1/2}$ with $n = 1, 2, 3$, where L_n and C_n are the inductance and capacitance per unit length, Z_{0n} is the characteristic impedance, V_{pn} is the phase velocity of each steps of the co axial line and Z_g is the waveguide impedance.

The mutual impedance transfer factor (m^2) given in the equivalent circuit representation of the mode launcher (Fig. 2(c)) is derived by using the surface currents on wheel (J_s)

$$m^2 = \frac{1}{I_0^2}\left(\iint j_s \cdot e_m^{01} ds\right)^2 \text{ for TM}_{01}\text{-mode}$$

$$m^2 = \frac{1}{I_0^2}\left(\iint j_s \cdot e_m^{02} ds\right)^2 \text{ for TM}_{02}\text{-mode}$$

With $J_s = U_r \frac{I_0}{d} \cos k(r)$, $-\pi < \phi < \pi$, where U_r is the normal vector in radial direction, d is the width of the spokes forming the wheel, $k = 2\pi/\lambda$, λ is the free space wavelength, and e_m^{0p} is the normalized vector mode function ($p = 1$ for TM_{01}-, and $p = 2$ for TM_{02}-modes respectively) as given in [2].

The expression for the real and imaginary part of the input impedance ($Z_{in} = r_{in} + jx_{in}$) seen at the reference plane 'A' as shown in Figs. 2(a) and 2(b)) is given in [2] can be written as,

$$r_{in} = \frac{m^2 Z_0 \tan^2 \beta_0 L}{Z_g \left(1 + \tan^2 \beta_0 L\right)} \tag{2}$$

$$j x_{in} = \frac{j \left(X_1 + X_2 + X_3 + X_4\right)}{Z_g} \tag{3}$$

where Z_0 is coaxial input impedance; β_0 is the propagation constant and L is the total length of the steps. X_1, X_2, X_3 can be determined from (1), and X_4 is given by

$$X_4 = \frac{r_{in} Z_g}{\tan(\beta_0 L)} \tag{4}$$

The magnitude of the reflection co efficient and VSWR at the reference plane 'A', seen by the co-axial line can be evaluated using (2), (3) and (4) as

$$|\rho_m| = \sqrt{\frac{r_{in}^2 + {x_{in}}^2}{r_{in}^2 + x_{in}^2} \frac{-1}{+1}}$$

The VSWR at the input port can be written as

$$VSWR = \frac{1 + |\rho_m|}{1 - |\rho_m|}$$

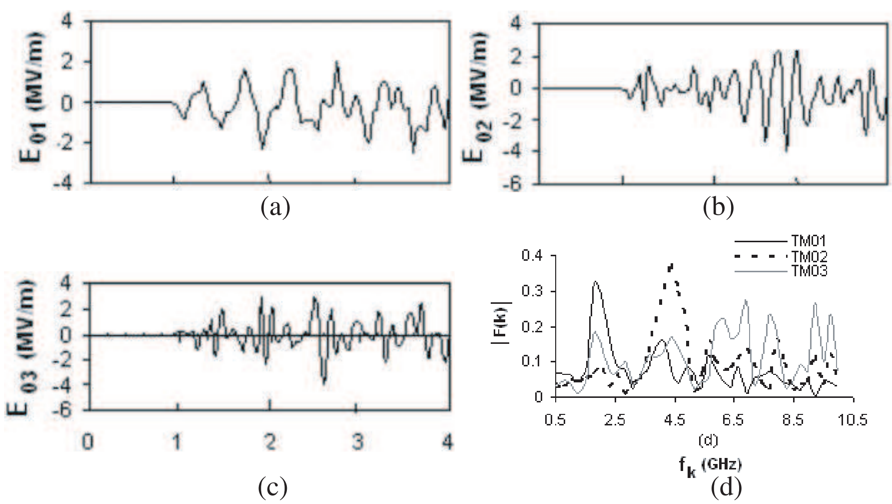

Figure 3. Hankel transforms for the first three transverse magnetic (a) TM_{01}, (b) TM_{02}, (c) TM_{03} modes, (d) their Fourier transforms.

Table 1. Simulation parameters of the vircator.

Beam voltage (kV)	250
Beam current (I_b) (kA)	8.2
Space-chare limiting current (kA)	0.819
Waveguide radius (mm)	75
Cathode radius (mm)	25
Anode-cathode gap distance (mm)	8
Anode radius at the grid (mm)	25
Axial and radial grid width (mm)	0.05
Pulse rise time (ns)	0.5
Pulse fall time (ns)	0.5
Total simulation time (ns)	4
axial electric filed Sampling time (ns)	0.05
No of particles/mm^3	1

3. MAFIA SIMULATION OF VIRCATOR

A particle-in-cell simulation of virtual cathode oscillator [6] has been carried out for the vircator specification given in Table 1, using a 3D electromagnetic simulation software package MAFIA. The problem has been run on a SUN-Micro workstation and typically took 60 seconds of run time. The simulation was carried out for extracting the total axial electric field. The Hankel and Fourier transforms have been carried out for the total electric field to find out the vircator excited frequencies using the equations [4] given in [1]. The results are shown in Fig. 3.

4. RESULTS AND DISCUSSION

The benchmarking of the proposed mode launcher design has been carried out with respect to 3D simulation in HP-HFSS, while further benchmarked against measurement. The benchmarking results are presented in Fig. 4. The measured VSWR shows good agreement with analytical and simulated results for TM_{01}-mode. But the measured VSWR shows less accuracy with analytical and simulated results for TM_{02}-mode due to the fabrication and assembly error for the TM_{02}-mode launcher.

The desired TM_{01} or TM_{02}-mode is launched into the waveguide coupler with the help of the appropriate mode launcher. The coupling factor for of couplers has been measured and the results were compared

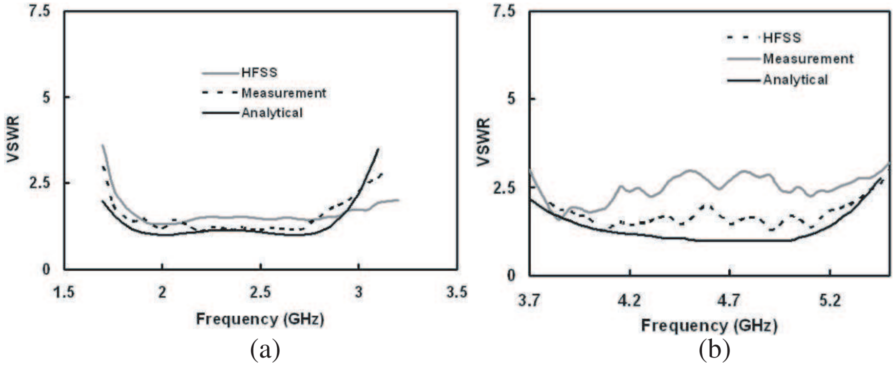

Figure 4. Comparison of VSWR plot for (a) TM_{01}-mode, (b) TM_{02}-mode.

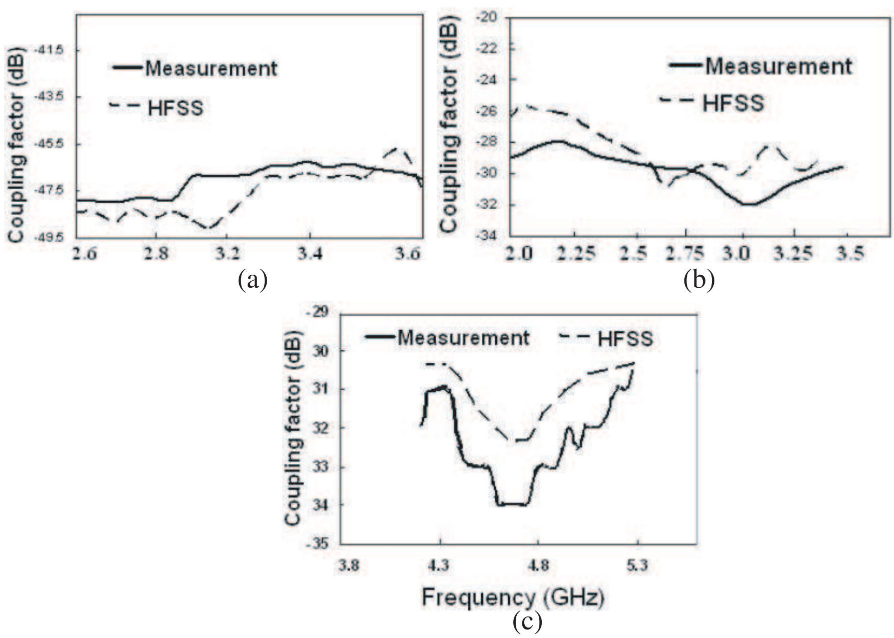

Figure 5. Comparison of Coupling (a) S-band wave guide elliptical iris coupler, (b) Co-axial coupler for TM_{01}-mode, (c) Co-axial coupler for TM_{02}-mode.

with numerical simulation results are shown in Fig. 5. The coupling factor lies between -49.5 dB and -46.5 dB for S-band waveguide iris coupling (Fig. 5(a)). Similarly, the coupling factor of the coaxial-probe

Table 2. Comparison of excited frequencies of a vircator.

Modes	Cut-Off frequency (GHz)	Excited Frequency (Simulation) (GHz)	Excited Frequency (Experiment) (GHz)
TM_{01}	1.53	2.05, 2.83	3.25
TM_{02}	3.54	4.38825	4.01
TM_{03}	5.51	6.92	7.0

coupler lies between $-30\,\mathrm{dB}$ and $-27\,\mathrm{dB}$ (Fig. 5(b)) for TM_{01}-mode. The coupling factor of the coaxial-probe coupler lies between $-34\,\mathrm{dB}$ and $-31\,\mathrm{dB}$ for TM_{02}-mode coupling (Fig. 5(c)). Hence, the designed couplers have maximally flat response of coupling factor within 3 dB throughout the desired bandwidth. Also, measured and simulated values of the coupling factor have agreed well.

The cold tested couplers have been used to couple the microwave from the vircator (Table 1) for the measurement of frequencies. The measurement was carried out using heterodyne method, using Tektronix oscilloscope TDS 520D with 500 MHz bandwidth and 1 Gs/Sec sampling rate. The comparison of the measured frequency with the simulation is given in (Table 2). The measured frequencies match with MAFIA-simulated frequencies of the vircator within 12.9%, 8.1%, and 1.1% for the TM_{01}, TM_{02}, and TM_{03} modes, respectively. Moreover, experimental as well as MAFIA-simulated values of the virtual cathode output frequencies are found to be close (i) to the limits 2.4 and 6.2 GHz set by the limits of the vircator oscillation frequency f_{oc} lying between f_p and $2.5f_p$, and (ii) to 6.95 GHz, the analytical value of the electron reflection frequency f_r [2].

5. CONCLUSION

Two TM_{0n}-mode couplers, namely, the waveguide type, which makes use of an elliptical aperture, and the tapered coaxial-probe type have been designed and qualified by suitable mode launchers. The couplers developed have successfully probed into wideband high power output of the vircator in single-shot experiments for the frequencies generated that agreed with MAFIA-simulation.

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