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13. ABSTRACT *(Maximum 200 words)*

High Power Microwave (HPM) and Vacuum Electronics (VE) sources have been studied in support of Air Force needs, under the auspices of the MiPRI initiative, a congressionally mandated program. A consortium of three universities led by the University of New Mexico and including the University of Michigan and MIT have teamed up to perform research on two sources of current interest to the Air Force: i) the relativistic magnetron operating at L-band for electronic attack, and ii) a novel W-band source concept in support of the active denial program. Technical progress on these activities is reported.

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High power microwaves, magnetrons, vacuum electronics, photonic bandgap structures

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I. INTRODUCTION

This Final Technical Report describes the research activities that were supported by the Congressionally-mandated AFOSR MiPRI program. In this collaboration led by the University of New Mexico, and including the University of Michigan and MIT, high power magnetrons were researched both experimentally and theoretically. Furthermore, possibilities of THz source development based on the Smith-Purcell effect and W-band source development using novel photonic bandgap structures were studied as well. Several publications were published based on this research program and are listed.

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Presentations/Publications

1. S. Prasad, M. Fuks, H. Bosman, and E. Schamiloglu, "Prospects for Long Pulse Generation in a Magnetron using a Transparent Cathode," *IEEE International Conference on Plasma Science* (Monterey, CA, June 2005).
2. S. Prasad, M. Fuks, H. Bosman, and E. Schamiloglu,"Rapid Onset of Oscillations in a Magnetron with a Transparent Cathode," *IEEE International Conference on Plasma Science* (Monterey, CA, June 2005).
3. E. Schamiloglu, "University Research Programs in HPM Sources and Technologies," (Plenary), *Tri-Service Vacuum Electron Device Workshop* (Albuquerque, NM, September 13, 2005).
4. H.L. Bosman, S. Prasad, M.I. Fuks, and E. Schamiloglu, "Priming Effects in a Relativistic Magnetron with a Transparent Cathode," *Bull. Am. Phys. Soc. DPP05*, C02 15 (2005).
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Synopsis of UNM Research

The University of New Mexico *Pulsed Power, Beams, and Microwaves Laboratory* has proposed that the "transparent cathode" (TC) can significantly improve the output of relativistic magnetrons [1]. The TC allows the azimuthal wave electric field to go to zero on-axis, thereby providing a strong field in the location of the electron sheath. The TC simultaneously provides cathode priming and magnetic priming, the latter which is a consequence of the self-magnetic field of the axial current on the discrete cathode emitters. In addition, the TC acts as an electrostatic wiggler in the sheath region. MAGIC particle-in-cell simulations of a relativistic magnetron and an Ubitron [2] powered by a TC were performed. Preliminary experimental results on the Ubitron configuration were performed and are reported as well.

There is ongoing interest in improving the output characteristics of high power microwave (HPM) sources [3]. Our recent efforts have been directed at crossed-field devices (with E_{0r} and H_{0z}) that are capable of generating high power microwaves (HPM), and use coaxial diodes with magnetic insulation (DMI) when the electromagnetic fields are absent. The magnetic insulation in the DMI is provided when the total magnetic field that is tangential to the cathode $H_0 = \left(H_{0z}^2 + H_{0\theta}^2\right)^{1/2}$ exceeds its critical value [1]

$$H_{0cr} = \frac{mc^2}{e}\frac{\operatorname{arccosh}\gamma_a}{R_c \ln(R_a/R_c)}, \tag{1}$$

which corresponds to the case where the external boundary of the Brillouin electron flow barely touches the anode surface with radius R_a [4]. In (1), $\gamma_a = 1 + eU/mc^2$; U is the applied voltage; R_c is a cathode radius; $H_{0\theta} = 2I_z/cr$ is the azimuthal magnetic field due to the axial current I_z of the diode; e and m are the charge and rest mass of an electron; and c is the speed of light. From (1) it follows that magnetic insulation can be provided without the external axial magnetic field, that is, with only the magnetic field $H_{0\theta}$, as is the case of the MILO [5].

A novel method for improving relativistic magnetrons and Ubitrons (free electron lasers-FEL's) is through the use of the TC [1]. The TC consists of individual emitters in the form of longitudinal strips periodically arranged about a fixed radius. The strips can be of any cross-section, and any geometric form, such as cylindrical, rectangular, or sectored rods. In this report we demonstrate the advantages of the TC for coaxial devices with applied crossed electrostatic and magnetostatic fields through computer simulations with the fully relativistic particle-in-cell code MAGIC [5], together with some preliminary experimental results.

In a DMI the electron sheath rotating around the cathode in the crossed fields exists together with the electrons comprising a leakage current. When a cathode with N individual emitters in the form of longitudinal strips periodically arranged about the cathode radius, electrons leaving the cathode flow in the axial direction in separate streams. The axial current I_{Nz} along each emitter produces transverse magnetic fields around them (Fig. 1), $H_{0\perp} = 2I_{Nz}/c\bar{r}$ (here $\bar{r}$ is radial distance from center of each emitter).

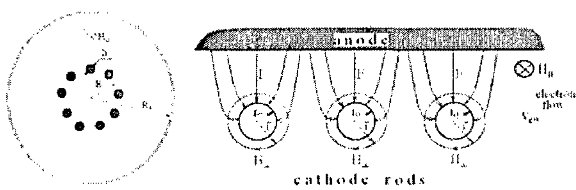

Fig. 1. Left: A DMI with a TC; right: periodic magnetic and electric fields near cathode rods in a DMI.

The electron sheath, therefore, moves in an additional periodic magnetostatic field produced by the TC wiggler. This leads to increasing transverse oscillations in the rotating electron sheath. For magnetrons, the periodic magnetic field which promotes faster grouping of electrons provides the same effect as magnetic priming [6] with periodically placed permanent magnets around a resonant system.

The start time of a magnetron is determined by (i) the noise-level from which the buildup of oscillations starts, and (ii) the rate of buildup [7]. This situation pertains to a magnetron with a solid cathode where the initial noise-level is ~ 10^{-10} of the electric energy of the electron sheath, and the time of instability onset in the symmetric electron sheath is several 10's of cyclotron periods [8]. Nonuniform emission from a solid cathode through an azimuthally periodic placement of emitters ("cathode priming") was suggested as a way to improve start conditions in a magnetron [9]. The azimuthal modulation in the electron sheath starts almost simultaneously with the start of electron emission, and a suitable choice of the number and position of regions of electron emission can promote the excitation of the desired operating mode. The TC automatically provides cathode priming.

The rate of buildup is determined by the azimuthal electric field E_θ of the operating wave that captures electrons in a resonant system. The TC provides the fastest start of oscillations. The TC is also a periodic slow wave structure in the coaxial cavity giving rise to azimuthal spatial harmonics of eigenmodes of the electrodynamic system.

In a magnetron, the azimuthal electric field of the operating wave synchronous with the rotating electron sheath is responsible for the radial drift of electrons from the cathode to the anode (which consists of a periodic resonant system). This drift is accompanied by a transfer of potential energy from electrons to the electromagnetic field. The average radial velocity of the electrons is $v_{er} = cE_\theta / H_0$. The field E_θ in the electron sheath rotating around the TC is much stronger than near the solid cathode (Fig. 2). Therefore, the formation of electron spokes (Fig. 3) and an increase of microwave oscillations (Fig. 4) in a magnetron with a TC is much faster than in a magnetron with a solid cathode with uniform electron emission, and also with non-uniform emission (cathode priming [9]).

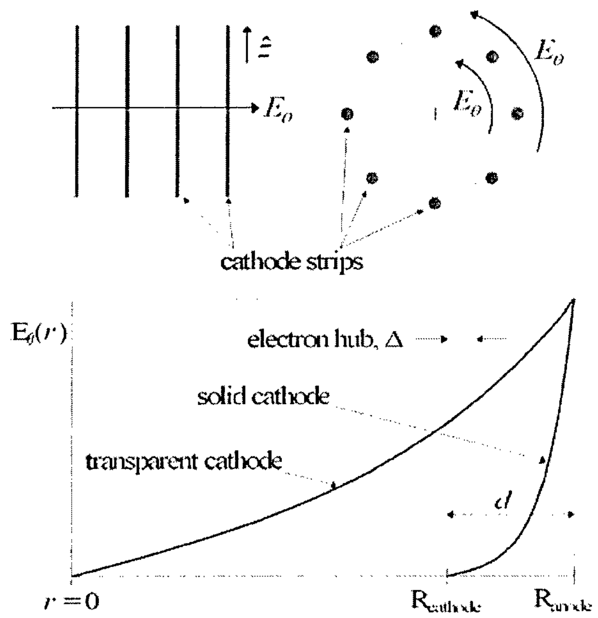

Fig.2. Top: view of transparent cathode and its discrete emitters; Bottom: distribution of electric field for a transparent cathode compared with a solid cathode.

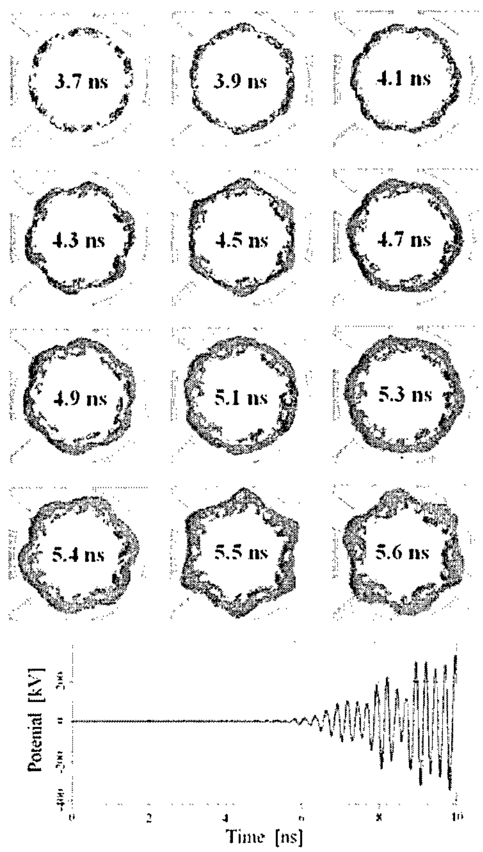

Fig. 3. Top: Particle plot during a voltage rise time of 10 ns for an A6 magnetron with a transparent cathode with 18 cathode strips (V = 350 kV, B = 0.55 T). Bottom: Voltage in the output waveguide.

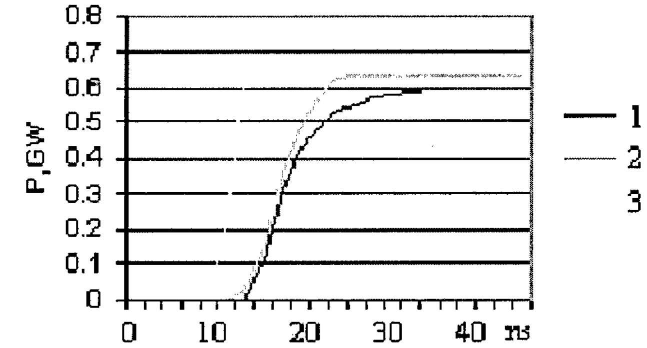

Fig. 4. Output power of the A6 magnetron with (1) a solid cathode, (2) solid cathode with cathode priming, and (3) TC when the applied voltage is U = 350 kV with rise time t_U = 10 ns and 2π-mode.

Higher efficiency can be achieved through a concomitant increase in the applied voltage and axial magnetic field. However, in a magnetron with a solid cathode this eventually leads to a degradation of the output characteristics [10]. The reason for this degradation is the decrease in the field E_θ in the electron sheath region (Fig. 2) that is responsible for the capturing of electrons to the anode. In a magnetron with a TC the field E_θ in the electron sheath is independent of its thickness (Fig. 2), which gives the possibility of decreasing the start time of oscillations and increasing efficiency.

An Ubitron in the form of a rippled field magnetron (RFM) suggested by Bekefi [2,11] consists of a smooth bore relativistic magnetron with additional periodic magnetic fields $H_\perp$ that are transverse to the axial direction z. In essence, this is a DMI in which the periodic field $H_\perp$ is produced by a set of periodic permanent magnets placed around the electrodes. Electrons drift around the explosively emitting cathode in this additional periodic field $H_\perp$ that is primarily radial near the center of the gap between electrodes; that is, the drift is in a transverse periodic magnetic field as in conventional FEL's.

The RFM has considerable interest [11-13] as a compact oscillator capable of generating short wavelength microwaves. However, the design of this wiggler is complicated, and the requirement to use a narrow gap (otherwise the magnetic field will basically be concentrated between adjacent magnets) leads to very large unwanted axial currents in this DMI. We propose an Ubitron that also uses a DMI; however, unlike the RFM, the wiggler is the TC itself. Such a wiggler is simpler and does not require a narrow gap. The radius of this cathode can be chosen so as to provide a suitable current. The maximum values of periodic magnetostatic and electrostatic fields occur in the region of the electron sheath, and the axial current from each emitter is not useless since they produce the periodic field $H_\perp$. Figure 5 presents the RFM with its periodic magnetic field configuration (top) and the radial distribution of the azimuthal electric field (bottom).

As with the magnetron, such a TC is transparent to TE modes that provide a strong azimuthal field E_θ in the electron sheath, unlike the RFM with a solid cathode. For TM modes the E_θ distribution in the Ubitron is as in the RFM. The periodic fields of the cathode-wiggler gives rise to azimuthal spatial harmonics for waves of the electron flow that can be in synchronism with eigenmodes of the electrodynamic system of the Ubitron.

In experiments (Figs. 6-8) microwaves were measured at a distance $L = 1.5$ m from the radiating horn antenna aperture, that is, in the far-field. Radiation power for each symmetrical radiation pattern was estimated as $P_1 \approx P_2 \approx$ 2 MW at 3.1 GHz, which is less than the cut-off frequency of the waveguide. Therefore, actual powers are much higher, since our diagnostics were measuring evanescent modes. This is being corrected for future experiments.

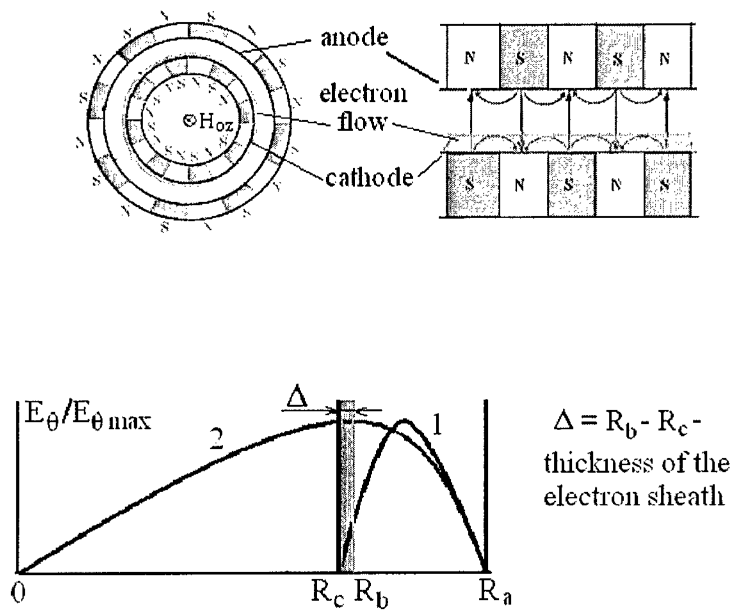

Fig. 5. Top: RFM and its magnetic field; distribution of E_θ in the Ubitron with a TC (bottom).In experiments (Figs. 4-6) microwaves were measured at a distance $L = 1.5$ m from the radiating horn antenna aperture, that is, in the far-field. Radiation power for each symmetrical radiation pattern was estimated as $P_1 \approx P_2 \approx$ 2 MW at 3.1 GHz, which is less than the cut-off frequency of the waveguide. Therefore, actual powers are much higher, since our diagnostics were measuring evanescent modes. This is being corrected for future experiments.

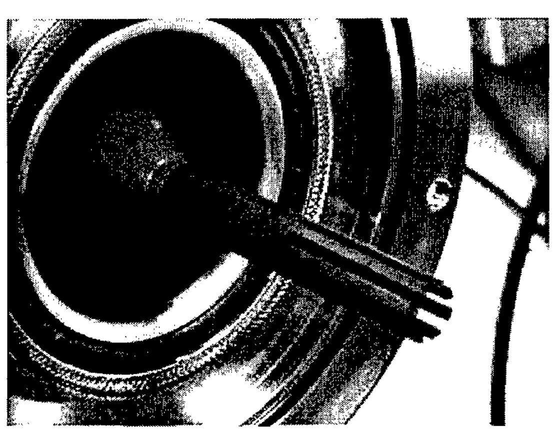

Fig. 6. Photograph of transparent cathode for ubitron experiments.

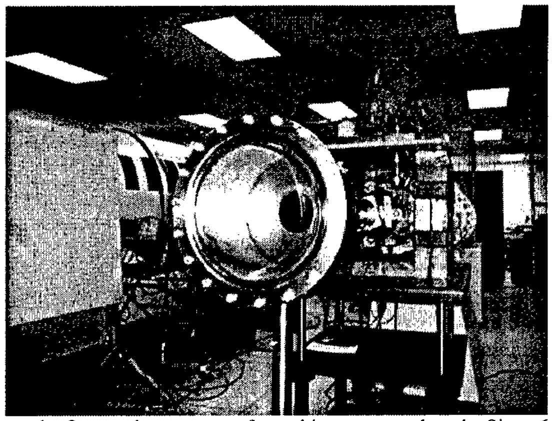

Fig. 7. Photograph of output horn antenna from ubitron mounted on the Sinus-6 accelerator..

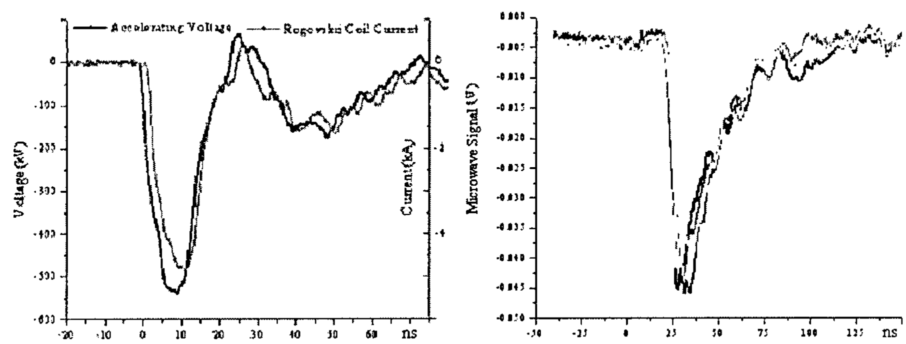

Fig. 8. Left: voltage and current traces; Right: overlay of 5 microwave power signals from ubitron.

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III. UNIVERSITY OF MICHIGAN

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Student: Ryan Edgar

Synopsis of Michigan Research

Experimental Progress

A three-section cathode was fabricated and experimentally tested that was intended to combine the concept of cathode priming with transparent cathodes. The Fig. 7 shows a photograph of the cathode. This cathode was fabricated by machining grooves in a solid aluminum rod; these grooves were painted with carbon to reduce secondary electron emission. The remaining, high, surfaces were micro-machined by the laser Ablated-Line-Focus (ALF) process to enhance electron emission. Preliminary results of this cathode on the UM-Titan relativistic magnetron were inconclusive.

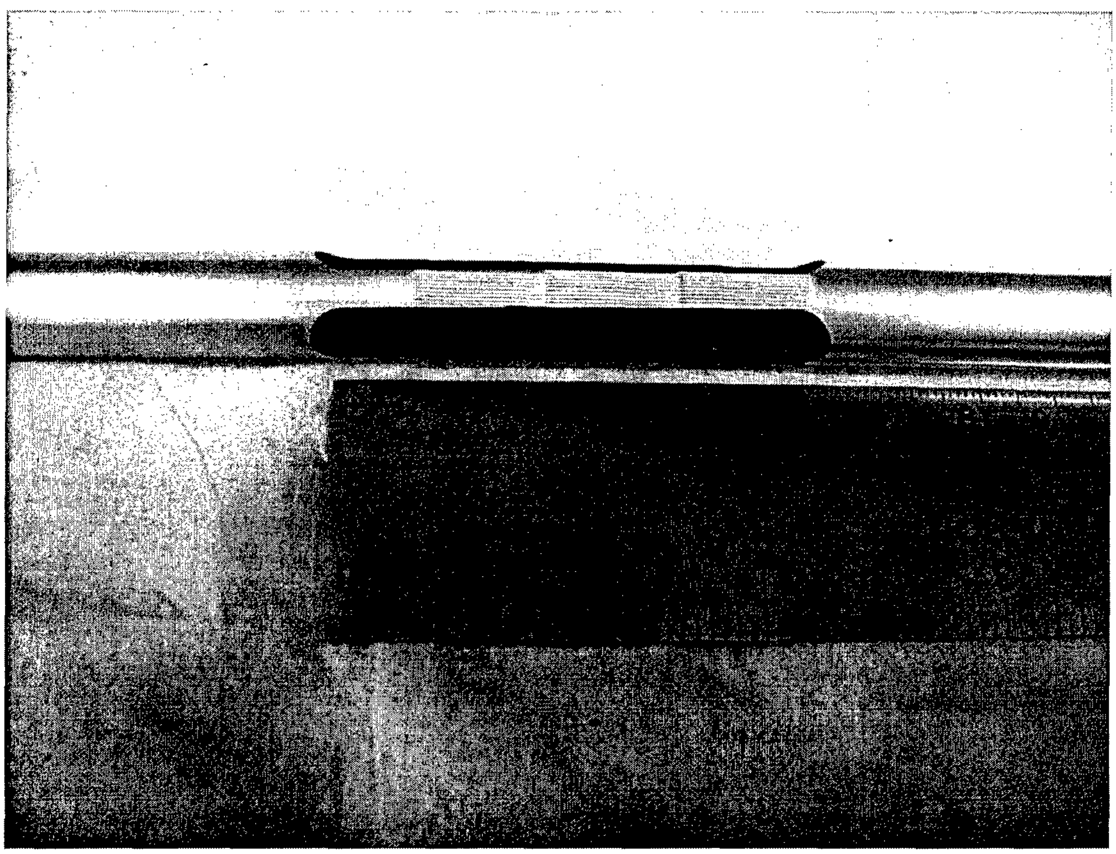

Fig. 7. Michigan PAL cathode used in magnetron experiments.

Studies were conducted to determine techniques to test the UNM transparent cathode on the UM-L-3-Titan magnetron driven by the MELBA generator. The basic question concerned the required magnetic field on the relativistic magnetron to utilize a full-size UNM "eggbeater-type" transparent cathode. It was determined that the existing UM magnetic field capacitor bank only allowed an eggbeater cathode with a diameter of 1.27 cm. In order to utilize a larger diameter cathode the magnetic field would need to be increased for the MELBA facility. Designs were developed for doubling the voltage of the capacitor bank that drives the MELBA electromagnets. Upgrades in the electrical insulation of the electromagnets were also implemented.

Theoretical progress

Studies of surface plasmons for THz generation:

There has recently been considerable interest in surface plasmons, which are collective modes of oscillation on highly conducting surfaces perforated by holes [1-3]. These modes have mostly been studied at high frequencies (optical) and low frequencies (GHz). During the MIPRI funding period, the feasibility of using surface plasmons as a coherent THz source was explored, in collaboration with U of New Mexico. No concrete results have been obtained thus far, however.

Three theoretical MiPRI projects are ongoing.

1. In collaboration with UNM/AFRL, we are examining various models of cathode priming, transparent cathodes, and optimization studies. Several visits by UM investigators to Albuquerque already took place. Such visits will continue during Lau's sabbatical beginning the Fall term.

2. We are studying the effects of manufacturing errors on the performance of microwave tubes. This issue is becoming more important as the tubes are being miniaturized.

3. Theoretical analyses on the effects of non-uniform work function on cathode emission will commence shortly, in collaboration with Kevin Jensen of NRL.

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IV. MIT

Personnel

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Synopsis of MIT Research

Under the auspices of the MiPRI program, MIT conducted a design study of an overmoded interaction circuit for a W-Band (94 GHz) slow-wave Traveling Wave Tube (TWT). The goals of the project included investigation of various kinds of interaction structures to obtain high interaction impedance and bandwidth. Furthermore, we also investigated interaction circuits made of a photonic bandgap (PBG) structure which would allow overmoded operation allowing the increase in average power by at least an order of magnitude over the current circuit approaches. They should also allow extension to higher frequencies, including THz frequencies. The design study was conducted for a W-Band vacuum electron device amplifier capable of 100 kW of power in short pulses using a novel, photonic bandgap (PBG) interaction structure.

Progress on the Device Circuit Design

In the first round of circuit design, we designed a proof-of-principle overmoded slow wave structure based on PBG elements, as shown in Fig. 8. The operating mode is TE_{310} which has three variations of the electric field in the transverse direction. In the figure, the hollow pipes are actually solid metal rods forming the PBG structure. The rod diameter in this preliminary design is 1.26 mm. With this choice of rod diameter, the circuit supports a higher order mode at 94 GHz. For frequencies in the band gap the PBG structure acts as a copper wall for the microwaves. The lower order competing modes at lower frequencies are not confined by the PBG structure and hence leak out of the structure. This frequency discrimination property of the PBG structure helps in the suppression of mode competition.

In the next step we investigated an overmoded variant of a ladder type slow wave structure as shown in Fig. 9. Such a structure offers moderate interaction impedance over a wide bandwidth while maintaining a flat phase velocity dispersion.

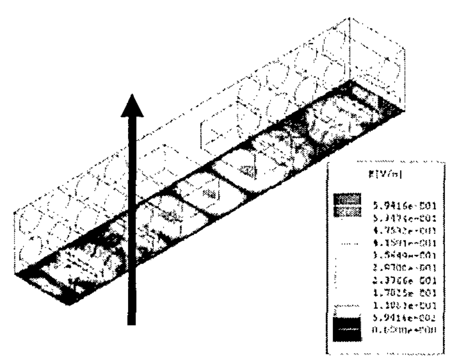

Fig. 8. HFSS model of an overmoded PBG interaction structure for a 94GHz TWT. The arrow shows the direction of the electron beam propagation.

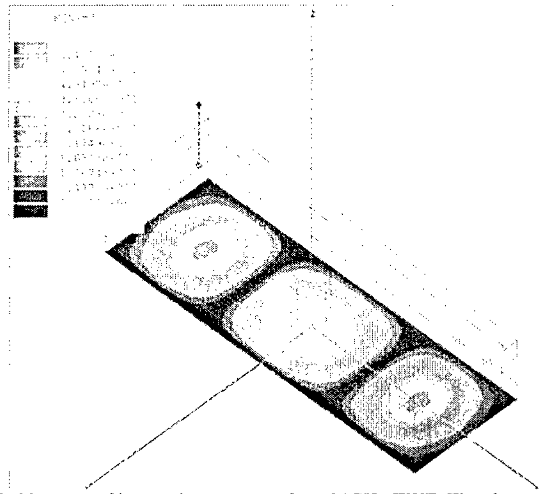

Fig. 9. HFSS model of an overmoded ladder type of interaction structure for a 94GHz TWT. The electron beam passes through the cylindrical beam tunnel.

Though the overmoded structure has slightly lower gain it can accommodate a much larger beam and hence more current resulting in higher gain. In our case we can accept an electron beam with a diameter of 1 mm, compared to 0.5mm used in a conventional W-band Millitron tube built by Bill James at CPI.

In future research, we plan to complete the design of an overmoded PBG ladder type of circuit. The interaction circuit can be designed such that it can be fabricated using conventional high precision machining to make the structure robust and reduce fabrication costs. Using a 60 kV, 2 to 4 A beam we estimate that up to 100 kW of power can be generated at 94 GHz with 30-40 dB gain. The choice of the operating mode and the design of the structure will be such that a future fully engineered device can operate at up to 20 % duty factor.

Table 1. Comparison of the interaction characteristics of an overmoded PBG ladder type structure (MIT Design) with a conventional fundamental mode ladder type structure (Millitron).

Frequency	**MIT Design TE_{310}**	**Low Power Millitron (CPI Inc.) TE_{110}**
Voltage (kV)	40	25
Current (A)	0.5	0.2
Perveance (μP)	0.0625	0.05
Beam diameter (mm)	1.0	~0.5
2.5 Brillouin Field (T)	0.21	0.30
Cavity Dimensions (mm)	2.15 x 6.35	3.1 x 1.6
Coupling slot dim (mm)	1.9 x 0.62	1.2 x 0.41
Beam tunnel diameter (mm)	1.2	0.61
Period (mm)	0.89	0.813
Interaction Impedance (Ω) (mid band, on-axis)	21	54
Gain (dB/cm) at synchronism	18.9	23.3
Loss (dB/cm)	0.84	0.94