**MAGIC3D Simulations of a 500-W Ka-Band Coupled-Cavity Traveling-Wave Tube**

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MAGIC3D Simulations of a 500-W Ka-Band
Coupled-Cavity Traveling-Wave Tube

Hae Jin Kim, Hyoung Jong Kim, and Jin Joo Choi

Abstract—The 3-D particle-in-cell (PIC) simulations of a Ka-band coupled-cavity traveling-wave tube (CCTWT) are shown. The computational analysis of the Ka-band coupled-cavity slow-wave structure was conducted through the use of an electromagnetic PIC code MAGIC3D. The choice of a double-slot staggered RF cavity circuit was made because of a wide frequency bandwidth, moderate interaction impedance, and excellent thermal dissipation properties. We investigated the large-signal and nonlinear beam dynamics of a Ka-band CCTWT using MAGIC3D. The center frequency of the Ka-band CCTWT can be tuned from 28.4 to 30 GHz by varying the cathode voltage. Hot-test simulations show that the 84-cavity Ka-band CCTWT produces 540 W of saturated output power at 29 GHz with an electronic efficiency of 8.1% and a gain of 28 dB when the beam voltage and current are set to 17 kV and 390 mA, respectively.

Index Terms—Double-slot staggered coupled cavity, MAGIC3D, traveling-wave tube.

I. INTRODUCTION

COUPLED-CAVITY traveling-wave tubes (CCTWTs) are microwave and millimeter wave amplifiers that are used extensively in communications and radar applications [1], [2]. High-power CCTWTs at Ka-band frequencies have been developed for military radar and satellite communication applications [3], [4].

Computer simulation and modeling have played an important role in the design and the calculation of cold-test performance of coupled-cavity TWTs [5]–[8]. The accurate representations of the electromagnetic fields are required in order to predict the performance of linear beam tubes. Both 1-D and 2-D models have been developed and implemented in large-signal codes to simulate CCTWTs [9]–[13]. These correspond to a large reduction in TWT development time and cost. The computational improvements afforded by a 3-D model result in potentially significant advances in the TWT design and development. The advantages of full-scale 3-D particle-in-cell (PIC) codes are that they theoretically provide a complete description of the electromagnetic fields. With the advent of modern computation, fully 3-D simulations involving millions of particles and cells have become possible [14]. In this paper, we present the design and simulation of a Ka-band double-slot staggered CCTWT based on CPI’s CCTWT [4] by using the 3-D PIC code MAGIC3D in order to investigate and understand the beam dynamics in the CCTWT. We simulated the Ka-band CCTWT in [4] by using similar parameters such as beam voltage, beam current, and slow-wave structure dispersion characteristics. MAGIC3D is a 3-D, fully dynamic, and self-consistent PIC code used to simulate plasma-physics problems [15]. We begin with the cold-test simulation to determine the dispersion characteristics of the CCTWT. Waves on an RF structure are characterized by its dispersion relation, relating resonant frequency, and wavelength. In Section II, the MAGIC3D simulation model of a reentrant double-slot staggered RF cavity structure is described in detail. With the simulation of 12 coupled cavities, the dispersion curve of the double-slot staggered coupled-cavity circuit is obtained through the relation of the phase shift and the resonant frequency using MAGIC3D. In Section III, we describe the hot-test simulation in the presence of an electron beam and predict the operating characteristics of the Ka-band CCTWT such as saturated RF output power, gain, and efficiency. Some concluding remarks are given in Section IV.

II. COLD-TEST SIMULATIONS

Fig. 1 shows a MAGIC3D model of a reentrant double-slot staggered RF millitron slow-wave circuit. The term “millitron” refers to a class of robust structures of rectangular geometry, which are easily fabricated for operation at millimeter wavelengths [16]. The coordinate system used in the simulation is a rectangular coordinate system (x, y, z), with positive z running along the axis of the CCTWT in the direction of the beam. The cavities have square-shaped cross sections. Fig. 1(a) shows a cutaway view of a double-slot staggered coupled-cavity slow-wave circuit in the direction of the beam travel. Fig. 1(b) shows the alternating cavity wall cross-sectional views A – A’ and B – B’. The coupling slots are cut into the walls that separate the cavities. The two coupling slots for each wall are rotated 180° from each other around the beam axis in the same wall. The slot location is altered by 90° for successive walls. As shown in Fig. 1(a), the planes A – A’ and B – B’ are separated by a cavity period of 1.8034 mm (71 mils), and the dimensions of the slow-wave circuit are summarized in Table I.

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H. J. Kim was with the Department of Wireless Communications Engineering, Kwangwoon University, Seoul 139-701, Korea. He is now with the Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139-4307 USA.

H. J. Kim and J. J. Choi are with the Department of Wireless Communications Engineering, Kwangwoon University, Seoul 139-701, Korea (e-mail: jinch@kw.ac.kr).

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Fig. 1. (a) Cutaway view of the Ka-band double-slot staggered coupled-cavity circuit. (b) Cross-sectional views of $A - A'$ and $B - B'$.

![Image](image-url)

Fig. 2. (a) Dispersion characteristics of the Ka-band double-slot staggered coupled-cavity circuit with beam velocity lines superimposed. (b) Interaction impedance with the total range of impedance shown for the 28.4 to 30 GHz bandwidth.

TABLE I

PARAMETERS OF KA-BAND DOUBLE-SLOT STAGGERED COUPLED-CAVITY CIRCUIT

<table>
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<tr>
<th>Design parameter</th>
<th>Dimensions</th>
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<tr>
<td>Cavity ($w$)</td>
<td>$4.6736 \times 4.6736$ mm</td>
</tr>
<tr>
<td>Cavity height ($l$)</td>
<td>1.1938 mm</td>
</tr>
<tr>
<td>Coupling slot ($S$)</td>
<td>$3.6576 \times 0.508$ mm</td>
</tr>
<tr>
<td>Slot height ($s$)</td>
<td>0.6096 mm</td>
</tr>
<tr>
<td>Cavity period ($f$)</td>
<td>1.8034 mm</td>
</tr>
<tr>
<td>Cavity gap ($g$)</td>
<td>0.5842 mm</td>
</tr>
<tr>
<td>Beam tunnel radius ($r$)</td>
<td>0.8128 mm</td>
</tr>
<tr>
<td>Nose radius ($R$)</td>
<td>1.3208 mm</td>
</tr>
<tr>
<td>Nose height ($h$)</td>
<td>0.3048 mm</td>
</tr>
</tbody>
</table>

Considering two consecutive cavities of the double-slot staggered slow-wave structure as a single-period resonator, we modeled a six-period resonator with 12 coupled cavities closed at both ends to obtain the dispersion curve of the Ka-band CCTWT. In the cold-test simulation without electron particles, the “EIGENMODE” command of MAGIC3D is used to search for resonant modes and frequencies. In such cases, all regions outside of the simulation region of interest are made perfectly conducting. The grid sizes used in the simulation are 0.05, 0.05, and 0.1 mm for $dx$, $dy$, and $dz$, respectively, where $dx$ and $dy$ are the transverse grids and $dz$ is the axial grid in the direction of beam propagation. The corresponding grid cell resolution is $50 \times 50$ cells in the $x-y$ plane and 18 cells per cavity in the axial direction. In the MAGIC3D simulations, the Maxwell algorithms solve Maxwell’s equations to obtain electromagnetic fields, which vary in time and space. The accuracy of the electromagnetic solution is determined primarily by the cell size relative to the wavelength.

The double-slot staggered coupled cavity is a fundamental backward wave circuit with the electron beam interacting with the first forward-wave space harmonic at an RF phase shift per cavity between $\pi$ and $2\pi$. The dispersion curve is obtained by the relation between the phase shift and the resonant frequency, as shown in Fig. 2(a). The cold bandwidth is approximately 10 GHz. The largest bandwidth circuit of the ladder core options is the double-slot staggered ladder [17]. Double-staggered slots were chosen because of this wide frequency bandwidth, ease of fabrication, and the moderate interaction impedance of Ka-band RF circuits. The wide cold bandwidth of the double-slot staggered circuit moves the high interaction impedance ends of the passband away from synchronism with the beam and, as a result, works to avoid amplifier oscillations.

The voltage tuning of the frequency range is shown in Fig. 2(a) by superimposing beam velocity lines corresponding to varying cathode voltages. The beam voltage, which is approximately 17 kV, is required for the synchronized interaction with the electron beam. Fig. 2(b) shows the Pierce on-axis interaction impedance for the first forward-wave space harmonic. This parameter is a measure of the strength of the interaction between an RF wave space harmonic and the electron beam. Calculations were conducted on the Pierce on-axis interaction impedance for the first forward-wave space harmonic. The Pierce on-axis interaction impedance for the $n$th RF space harmonic is expressed as [18]

$$K_n = \frac{E_n^2}{2\beta_n^2 P_{rf}}$$  

where $E_n$ is the axial electric field magnitude of the $n$th space harmonic, $\beta_n$ is the corresponding phase constant, and $P_{rf}$ is the RF power flow through the coupled cavity. The effective field as seen by the electron beam is the peak value of the
particular space harmonic with which the beam is synchronous. The value of this field for a traveling wave $E_n$ is half that of a standing wave $E_{ns}$. Using the “EIGENMODE” function of MAGIC3D, the peak value of axial electric field at each resonant mode can be obtained. The power flow $P_{rf}$ is given by

$$P_{rf} = W_{tot} \nu_g = \frac{W_s}{2NL} \nu_g$$

(2)

where $W_{tot}$ is the total stored electromagnetic energy per unit length for the traveling wave, and $W_s$ is the total electromagnetic energy of the standing wave. $N$ represents the number of resonant cavities, and $L$ is the length of one period of the periodic structure. $\nu_g = d\omega / d\beta_1$ is the group velocity. The group velocity is obtained by taking the derivative of the frequency-phase dispersion curve at each resonant frequency. In MAGIC3D simulations, the total electromagnetic energy for a standing wave is normalized to 1 W.

Fig. 3 shows the MAGIC3D model of the full 84-cavity Ka-band CCTWT with four ports, including couplers, to check the transmission and isolation characteristics of the RF wave. The total interaction circuit length is 15.41 cm. As shown in Fig. 3, the first section consists of 38 cavities, and the second section consists of 46 cavities. The first section provides a means of modulating the electron beam. The modulated beam induces an RF wave on the second section. This RF wave and the beam interact in the second section to produce additional gain. Reflections at the circuit discontinuities such as the input and output rectangular waveguide couplers can cause regenerative oscillation in TWTs. Extrinsic attenuation and severs are used to suppress these reflections [19]. Output ports 1 and 2 are used as severs for suppressing regenerative oscillations caused by reflected waves.

We first simulated cold-test conditions (no electron beam) by launching RF into the input port and determining the power at the three output ports. The launched RF signal at the waveguide input port propagates through the coupled-cavity circuit. The dominant mode of the rectangular coupled cavity is the $TM_{110}$ mode. An acceptable impedance match over the operating frequency band was achieved by adjusting the waveguide dimensions of the stepped impedance transformers [20].

Fig. 4 shows the voltage standing wave ratio (VSWR) and RF transmission ratios for the double-slot staggered slow-wave circuit to waveguide coupler for the first section shown in Fig. 3. As shown in Fig. 3, the RF signal from the input port travels to output port 1. The simulation predicts that the RF transmission ratio defined as $(P_{out}/P_{in})$ in the range of 28.4 to 29.8 GHz is higher than 90%. At 30 GHz, the calculated transmission power ratio is about 86.1%. This value corresponds to a reflection coefficient $(\Gamma)$ of 0.372, a return loss of 8.58 dB, and a worst case VSWR of 2.18. Reflection coefficient and VSWR are calculated as

$$P_{out} = P_{in} (1 - \Gamma^2)$$

(3)

$$\text{VSWR} = \frac{1 + \Gamma}{1 - \Gamma}.$$  

(4)

Fig. 5 shows the RF transmission and isolation characteristics versus time at 29.2 GHz. The negative value of input power means that power flow travels into the circuit through the arrow direction at the input port, as shown in Fig. 3. When the power at the input port is 732 mW, the transmitted power through output port 1 is 730 mW. Moreover, the RF powers measured at output ports 2 and 3 are 0.08 and 0.096 mW, respectively.
This demonstrates that the first and second sections are well isolated.

III. HOT-TEST SIMULATIONS

The hot-test simulations of the 84-cavity CCTWT were performed in the presence of an electron beam using MAGIC3D. The total number of cells and the total number of particles involved in the simulations are approximately seven million and one million, respectively. Simulations were carried out on a single PC equipped with the Intel E6420 CPU. One simulation of 30 ns requires approximately one day of CPU time.

Fig. 6 shows the phase space of the electron beam of the Ka-band CCTWT. Fig. 6(a) shows the beam bunching in the $x-z$ plane as a function of the axial position at the end of the simulation. Since the wave and the electron bunches are traveling at approximately the same velocity, the electrons experience a continuous deceleration along the slow-wave circuit. This continuous interaction results in a continuously increasing wave amplitude at the output port 3 of the CCTWT. Fig. 6(b) and (c) shows the axial momentum of the electron macroparticles and the average kinetic energy of the particles versus the circuit length, respectively. As shown in Fig. 6(b), the low axial momentum of particles near the circuit end means that electrons lose their kinetic energy. The kinetic energy lost by these electrons is transferred to the outgoing RF wave through output port 3. As shown in Fig. 6(c), the rapid energy extraction occurs near output port 3. Simulations were performed with a beam voltage of 17 kV, a beam current of 0.39 A, and a beam diameter of 0.81 mm. An axially uniform magnetic field with 2 kG, which is higher than the calculated Brillouin field of 1.2 kG, is used to confine the beam in the CCTWT.

Fig. 7 shows the time-average integrated Poynting vectors determined at the four waveguide ports as a function of time. We obtained a saturated output power of 540 W with an input drive power of 720 mW at 29 GHz. The corresponding power at output port 1 is about 30 W, and the reflected power at output port 2 is about 3 W. We compared the input and three output powers of the 84-cavity Ka-band CCTWT in the presence of an electron beam for the following two cases: 1) rapid beam turn-on and 2) slow beam turn-on. Fig. 7(a) shows that the input power reaches the steady state value of 720 mW within 3 ns, following an initial spike. This time denotes the round trip time of a traveling wave from the input port to the output port 1 through the 38 coupled-cavity circuits of the input section. After 3 ns, the power measured at the input port becomes slightly tilted due to the reflected wave power. In the case of a slow beam turn-on, the spike signal near 3 ns disappears. In the presence of an electron beam, the power measured at the input port is different from when no electron beam is present. As shown in Fig. 3, the input power measured at the input port is constant in the cold-test simulation. However, with an electron beam present, the input power is increased slowly after 3 ns,
as shown in Fig. 7(a). Fig. 7(a) shows that there are two power flows at the input port: one is the power going into the input port, which then goes into the circuit, and the other is the power coming out of the input port, which is reflected from the circuit. This means that the gradually increasing input power results from a gradually increasing amount of reflected power from the circuit to the input port. We also compare the powers measured at output ports 1, 2, and 3 with respect to the beam turn-on transient, as shown in Fig. 7(b)–(d). Interestingly, there is not a similar power tilt over time at output port 2 as there is at the input port.

Fig. 8(a) and (b) shows the time response of the RF voltages integrated along the center lines of the four waveguide ports and their fast Fourier transforms (FFTs). The operating frequency is 29 GHz. The RF voltage measured at output port 3 is about 780 V, yielding an output power of 540 W. As shown in Fig. 8(b), the FFT indicates that the input and output frequencies remain the same and the RF signal at output port 3 is amplified. At a drive power of 0.72 W, the Ka-band CCTWT produces 540 W of output power at 29 GHz with an efficiency of 8.1% and a gain of 28 dB when the beam voltage and current are 17 kV and 390 mA, respectively.

To find saturation, Fig. 9 shows the output power as a function of input power at five different cathode voltages and corresponding drive frequencies. The cathode voltages are 17.2, 17.1, 17.0, 16.9, and 16.7 kV, and the input frequencies are 28.4, 28.8, 29.2, 29.6, and 30 GHz, respectively. At each frequency, the CCTWT is driven to an output power of approximately 57 dBm. This demonstrates the voltage-tuned bandwidth of the Ka-band CCTWT.

Fig. 10 shows the comparison of saturated output power and gain versus frequency for the three fixed beam voltages: 16.8, 17, and 17.2 kV. In all the three cases, the beam current and the axial magnetic field are 390 mA and 2 kG, respectively. At a beam voltage of 17.2 kV, the saturated output power is higher than the other two cases over the frequency range from 28.4 to 29.6 GHz. At a fixed cathode voltage, the saturated CCTWT bandwidth is approximately 28.4 to 29.8 GHz or 1.4 GHz (5%). By tuning the cathode voltage from 16.7 to 17.2 kV, the RF output occurs over different frequency bands that have center frequencies between 28.4 and 30 GHz. Fig. 11 shows the center-band saturated output power, input drive, and gain as the cathode voltage is tuned from 17.2 kV (28.4-GHz center-band frequency) to 16.7 kV (30.0-GHz center-band frequency). The saturated gain of the CCTWT is...
of a CCTWT means that the saturated power can be tuned to RF waves over different frequency bands. This characteristic cathode voltage results in synchronization of the beam and 9 dB lower at 30 GHz compared to 28.4 GHz. Changing the frequency).

changing the center-band frequency as the cathode voltage is tuned from 16.7 kV (28.4-GHz center-band frequency) to 17.2 kV (30.0-GHz center-band frequency) to 16.7 kV (28.4-GHz center-band frequency).

Fig. 11. Saturated output power, input drive, and gain of the Ka-band CCTWT at the center-band frequency as the cathode voltage is tuned from 16.7 kV (30.0-GHz center-band frequency) to 17.2 kV (28.4-GHz center-band frequency). 9 dB lower at 30 GHz compared to 28.4 GHz.

Changing the cathode voltage results in synchronization of the beam and RF waves over different frequency bands. This characteristic of a CCTWT means that the saturated power can be tuned to different frequencies by tuning the cathode voltage.

IV. CONCLUSION

MAGIC3D PIC simulations have been performed to investigate the beam dynamics of a Ka-band double-slot staggered CCTWT based on an existing CPI-developed 500-W PPM-focused CCTWT. It is believed that this is the first time that 3-D PIC simulations have been conducted for a full-scale double-slot staggered CCTWT. The CPI CCTWT is capable of greater than 500-MHz instantaneous bandwidth and is cathode voltage tunable from 28.3 to 30 GHz. Hot-test simulations predict similar performance—that the Ka-band double-slot staggered CCTWT produces 500-W RF output power and has a cathode-voltage-tunable frequency range from 28.4 to 30 GHz. The detailed beam dynamics of the 500-W double-slot staggered Ka-band CCTWT are predicted by the MAGIC3D simulations. These results suggest that the MAGIC3D PIC code is a useful tool for predicting the performance of high-power CCTWTs.

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REFERENCES


Hae Jin Kim received the B.S. degree in electronic engineering and the M.S. and Ph.D. degrees in wireless communications engineering from the Kwangwoon University, Seoul, Korea, in 2000, 2002, and 2008, respectively. He is currently working as a Postdoctoral Fellow with the Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge. His research interests include high-power vacuum devices, including traveling-wave tube, gyro traveling-wave amplifier, magnetron, and klystron.

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Hyoung Jong Kim received the B.S. degree in electrical engineering in 2006 from the Kwangwoon University, Seoul, Korea, where he is currently working toward the Ph.D. degree in wireless communications engineering.

His research interests include highly efficient solid-state power amplifier, TWT and MPMs for radar, and wireless communications.

Jin Joo Choi received the B.S. degree in physics from Seoul National University, Seoul, Korea, in 1983, the M.S. degree in physics from Georgia State University, Atlanta, in 1985, and the Ph.D. degree in nuclear engineering from the University of Michigan, Ann Arbor, in 1991.

In 1991, he was with the Vacuum Electronics Branch, Electronic Science and Technology Division, U.S. Naval Research Laboratory (NRL), Washington, DC. His work at the NRL was on the development of high-power millimeter-wave gyro amplifiers for electronic warfare and radar applications. Since 1997, he has been with the Kwangwoon University, Seoul, where he is currently a Professor with the Department of Wireless Communications Engineering. His research interests include high-power vacuum electronics and passive and active solid-state devices.