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14. ABSTRACT
In this project we pursue the development of a novel miniature submillimeter-wave magnetron oscillator (SMO) which combined vacuum tube technology with solid-state microfabrication technology. The SMO is a compact, rugged and lightweight terahertz source capable of operating in the nearly unexplored near- and far-infrared electromagnetic spectrum. It will provide high power, highly efficient THz radiation for active illumination and/or local oscillators for applications in compact sensor arrays for THz imaging. Civilian applications of these devices

15. SUBJECT TERMS
Miniature Sub-millimeter Wave Magnetron Oscillator

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Report Title

Miniature Sub-millimeter Wave Magnetron Oscillator

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In this project we pursue the development of a novel miniature submillimeter-wave magnetron oscillator (SMO) which combined vacuum tube technology with solid-state microfabrication technology. The SMO is a compact, rugged and lightweight terahertz source capable of operating in the nearly unexplored near- and far-infrared electromagnetic spectrum. It will provide high power, highly efficient THz radiation for active illumination and/or local oscillators for applications in compact sensor arrays for THz imaging. Civilian applications of these devices include high-resolution radar, satellite telecommunications, remote sensing, line-of-sight networking, plasma and solid-state diagnostics, and high-speed computing. Other military applications of the SMO include line-of-sight networking and communications as well as chemical and biological spectroscopy. In the SMO, a tiny electron beam produced by a micron-sized cold-cathode interacts with the millimeter-wave fields of a miniature multi-vane cylindrical microcavity where the beam, as it rotates about the cavity axis, generates a terahertz signal inside the microcavity. The highly desirable features of the SMO, such as high power and its miniature size, make for an ultrahigh frequency vacuum microtube that has the potential to revolutionize the millimeter-wave tube industry. Once fully developed, the SMO should represent a multi-million dollar market.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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Patents Awarded

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Names of Post Doctorates

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Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Scott Barker	1.00	No
FTE Equivalent:	**1.00**	
Total Number:	**1**	

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Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
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Total Number:

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14. ABSTRACT
During this Phase II SBIR project we aggressively pursued the development of a novel Nanomagnetron source using theoretical, numerical and experimental studies. The main subsystems of this source were successfully designed and built. We fabricated a permanent magnet capable of producing a magnetic field with an intensity of up to 1.8 T. In addition, the design and fabrication of a nanotube cathode assembly was also completed. Finally, a miniature rising-sun cavity capable of operating at 94 GHz was also designed and successfully fabricated using pioneering microfabrication techniques. Details of the fabrication of this unique system are presented.

15. SUBJECT TERMS
High-power, miniature, sub-millimeter, oscillator, magnetron, vacuum.

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"Miniature Sub-Millimeter Wave Magnetron Oscillator"

Final Report
Item No 0002

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In this project we pursue the development of a novel miniature submillimeter-wave magnetron oscillator (SMO) which combined vacuum tube technology with solid-state microfabrication technology. The SMO is a compact, rugged and lightweight terahertz source capable of operating in the nearly unexplored near- and far-infrared electromagnetic spectrum. It will provide high power, highly efficient THz radiation for active illumination and/or local oscillators for applications in compact sensor arrays for THz imaging. Civilian applications of these devices include high-resolution radar, satellite telecommunications, remote sensing, line-of-sight networking, plasma and solid-state diagnostics, and high-speed computing. Other military applications of the SMO include line-of-sight networking and communications as well as chemical and biological spectroscopy. In the SMO, a tiny electron beam produced by a micron-sized cold-cathode interacts with the millimeter-wave fields of a miniature multi-vane cylindrical microcavity where the beam, as it rotates about the cavity axis, generates a terahertz signal inside the microcavity. The highly desirable features of the SMO, such as high power and its miniature size, make for an ultrahigh frequency vacuum microtube that has the potential to revolutionize the millimeter-wave tube industry. Once fully developed, the SMO should represent a multi-million dollar market.

Concept Description

The simplified geometry of the SMO is shown in Fig. 1. The basic device is composed of a miniature cold-cathode electron emitter, a microcavity with a set of equally-spaced vanes inside of it, a compact permanent magnet, and an output waveguide.

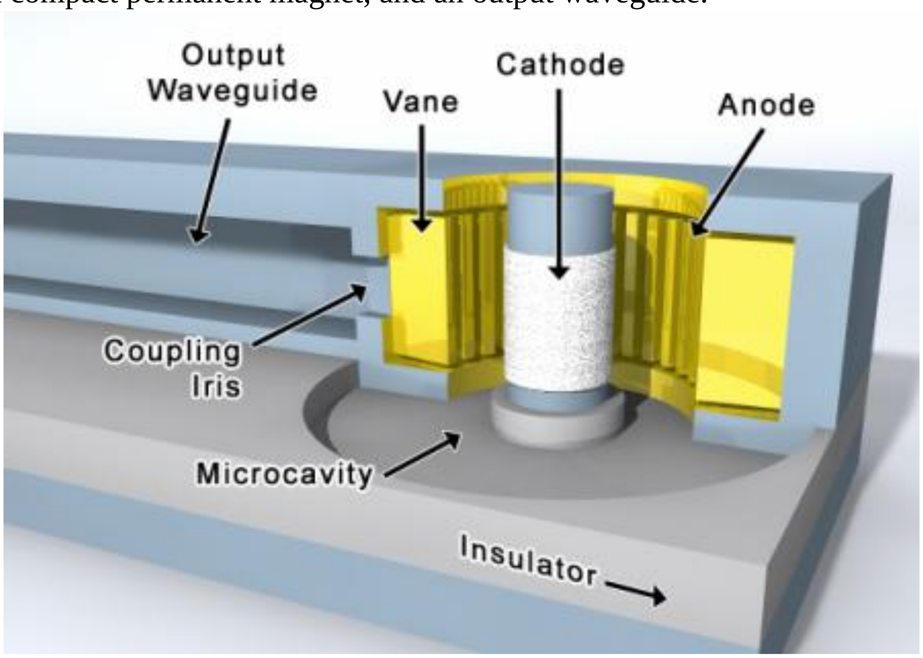


Figure 1: Simplified schematic of the miniature SMO terahertz source.

By applying a dc voltage between the cathode and anode, a tiny radially-moving electron beam is produced by the cold-cathode. The dc magnetic field generated by a permanent magnet bends the electron orbits and makes the electrons gyrate about the cavity axis. At quasi steady-state, the electrons form a cloud around the cathode. Electrons located in the outer border of the cloud, as they gyrate azimuthally, excite submillimeter-wave fields inside the cavity cells. As electrons interact with the fringe fields of the wave, they gradually lose energy to the fields. This energy loss makes the electrons' orbits become increasingly larger making them exit the cloud and eventually strike the cavity structure. It turns out that only a set of properly-phased electrons undergo these dynamics. Thus, at steady-state, the cathode only replenishes the amount of electrons lost to the cavity wall. This makes for a very efficient interaction and a very efficient device. Once the tube reaches steady-state operation, multi-milliwatt stable terahertz radiation is obtained along the SMO's output waveguide.

The goal was to construct the SMO using state-of-the-art solid-state microfabrication techniques. Thus, this development was a pioneering step towards the development of miniature vacuum tubes for ultra high-frequency applications.

The Phase II work plan for the nanomagnetron may be summarized by two statements. One is the fabrication of a cylindrical multi-vane magnetron cavity structure including output waveguide using solid-state micro-fabrication techniques with dimensions and specifications suitable for operation at 220 GHz. The second is to design and to fabricate a nanotube cathode (approximately 200 micron radius) capable of producing approximately 20 mA of beam current with an anode voltage of 2 kV in order to provide on the order of 100 mW microwave power. Consequently, this project had the goal of developing the highest frequency magnetron (capable of being a production device) with its ruggedness, high efficiency, and relatively low cast for millimeter-wave devices. The project also has some major challenges to address including, the need for a very intense (small volume) magnetic field higher than the levels found in any current device, the production of the first microwave device to use nanofabrication technology (University of Virginia), and the first use of a cylindrical micron-sized nanotube cathode. In addition, there were other critical issues to be considered such as mode control, local heating of the tiny vanes, and assembly tolerances. Some of these issues were discussed at a kickoff meeting with Dr. Dev Palmer of ARL/ARO, Dr. Scott Barker and Mr. Charlie Smith of the University of Virginia, and Drs. Murray Black, Willi Schwarz, and Jose Velazco, of MTI.

One major conclusion of this initial meeting was that in view of the challenges (and rewards) of building such a high frequency device, it was agreed that it would be a good idea to build a 94 GHz device first. Then applying the lessons learned from the lower frequency device, and if time and funds would permit, we could build a device scaled up to 220 GHz. The consensus was that much valuable science can be learned from the lower frequency (94 GHz or even 60 GHz) device. The view expressed was that frequency is not the major issue, progress at 94 GHz using the SU8 nanofabrication alone would be a significant achievement.

Another outcome of the kickoff meeting was to modify the initial design for the 94 GHz magnetron reported both in an earlier report and at the meeting. In order to reduce the complexity of the nanofabrication for the first prototype device, the major modification was to reduce the number of vanes from 36 to a smaller number such as 26. In addition to reducing the number of vanes, we also wanted to increase the vane thickness in order to improve the mechanical properties, improve heat dissipation, and reduce sensitivity to fabrication dimensional tolerances.

In the following three plots we examine briefly the consequences of reducing the number of vanes. As we have done in the past, in each of the plots there is reference made to the "optimum (opt)" and "minimum (min)" conditions for the magnetic field strength. In order for the applied magnetic field to be considerably in excess of the Hull (or cutoff) value, the voltage, V_B, associated with the so-called Brillouin cloud of electrons around the cathode should be between 10 to 20 percent of the cathode-anode voltage, V_A. Equivalently, it is desired to have the value of V_B / V_A between 0.1 and 0.2. The "optimum" value here refers to 0.15 and the "minimum" value refers to 0.2. The other condition is to ensure that the microwave fields at the skin of the Brillouin cloud (where the electrons travel synchronously with the rf field) should be at the appropriate level to ensure that there is a proper rf current. Typically for this to occur, $\omega (r_a - r_c) / v_p \sim 4$ to 8, where v_p is the phase velocity which is rough the velocity of the electrons at the skin of the Brillouin layer. The "optimum" value here refers to 6 and the "minimum" value refers to 8.

One consequence of this reduction of vanes is to increase the required voltage. As shown in Fig. 2, for a cathode size of 200 microns, the change in the number of vanes has a significant change in the required anode (to cathode) voltage. For example, from 36 vanes to 26 vanes the anode voltage requirement roughly doubles from 1.0 kV to nearly 2.0 kV. The hope was to keep this voltage around 1 kV for the initial device, but this must be relaxed in order to reduce the number of vanes.

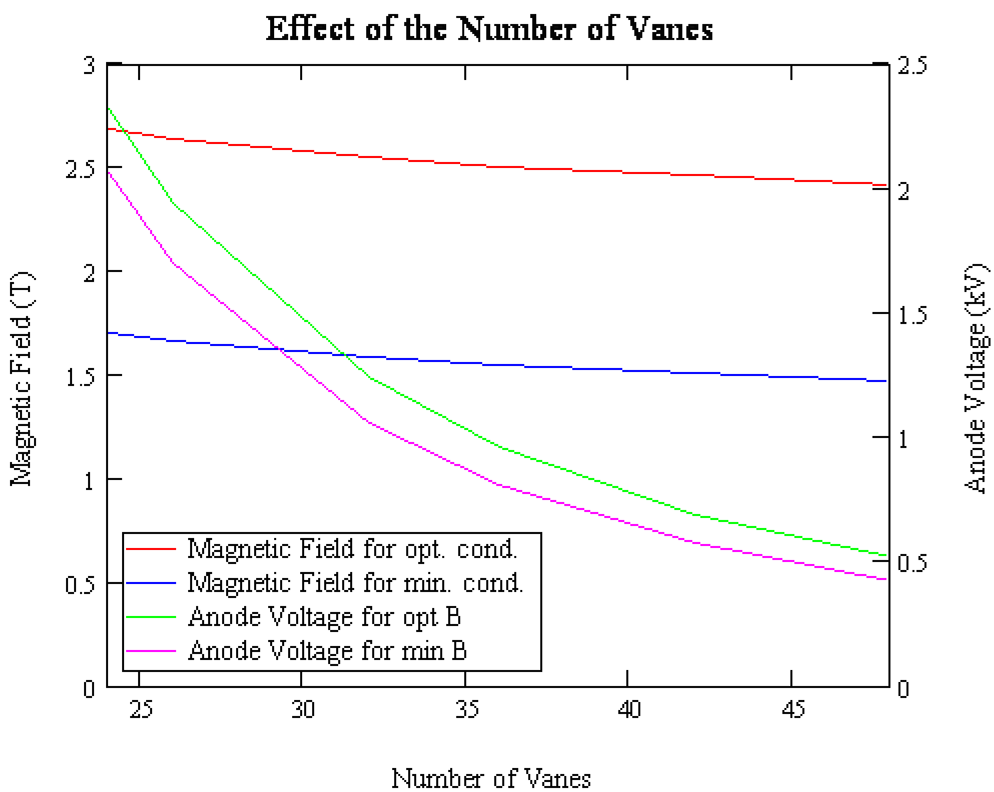


Figure 2: Plots of magnetic field and anode voltage as a function of number of vanes for a 94 GHz design. The cathode radius is set to 200 microns.

Figure 2 also shows that for a certain level of performance, the reduction of the number of vanes also slightly increases the need for magnetic field strength.

In order to reduce the voltage requirement, one alternative is to reduce the cathode size as shown in Fig. 3. But this becomes counterproductive in increasing the device size to assist in the manufacturing process.

As expected the reduction of the number of vanes for a given cathode radius has the desired effect of increasing the vane separation. As shown Fig. 4 for a cathode radius of 200 microns, for a reduction of the number of vanes from 36 to 26, the vane separation increases roughly from 50 microns to 80 microns. Note that this separation value includes both the width of the vane and the opening into the vane cavity. Typically, the vane width is anywhere from 1/3 to 2/3 of the total separation.

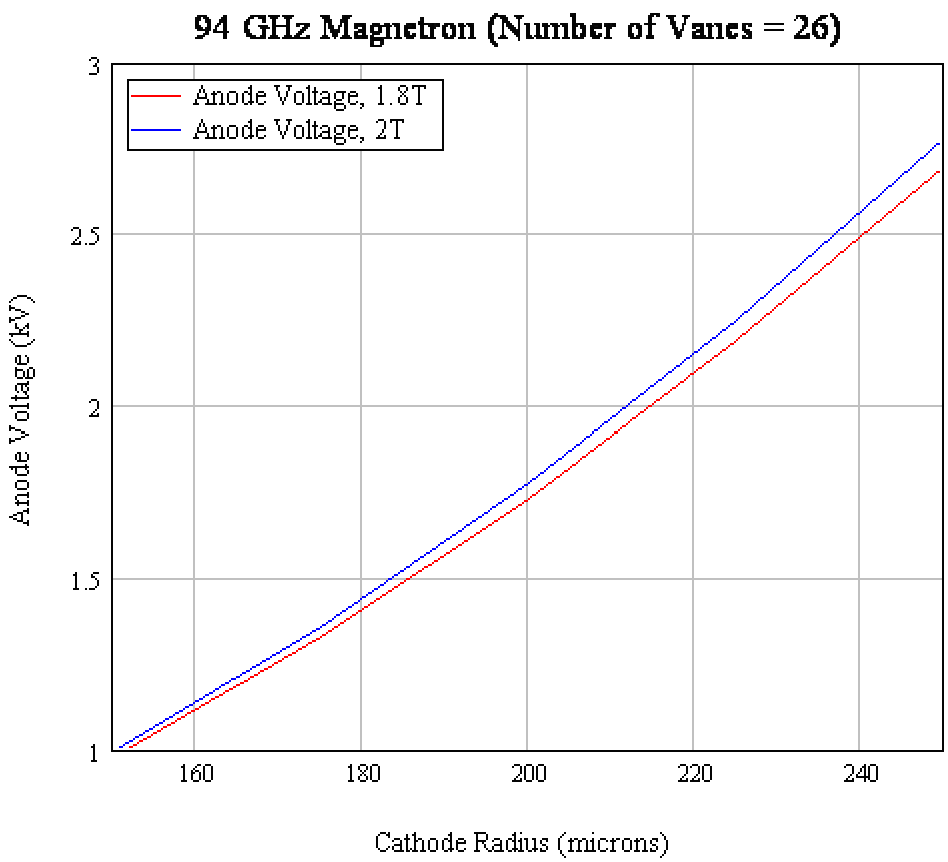


Figure 3: Plots of anode voltage as a function of cathode radius for a 94 GHz design for 2 cases of anode voltage. The number of vanes is set to 26.

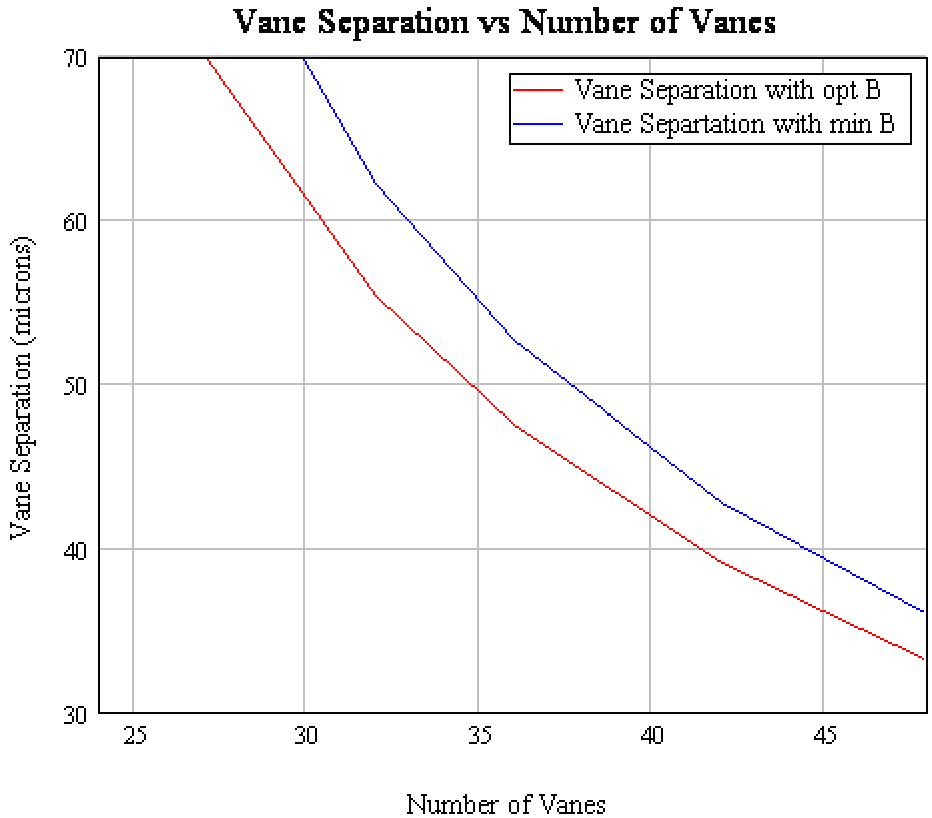


Figure 4: Plots of anode vane separation as a function of number of vanes for a 94 GHz design for 2 cases of magnetic field. Cathode radius is set to 200 microns.

Based upon these results of the variations of various parameters for the 94 GHz prototype magnetron, the conclusion was that the selection of 26 vanes was a reasonable choice to ease the fabrication of the initial device. Although we hoped to go higher in magnetic field, an initial selection of 2.0 T was hopefully one that could be achieved in this project.

During this project we were able to design a permanent magnet capable of producing a magnetic field of 1.8-2 T. These results are shown later on this report. Table I provides a range of some of the physical dimensions and experimental values for two values of magnetic field, 1.8 T and 2.0 T. Note that in this chart the value of the current density has been reduced from 5 A/cm^2 (as reported in previous reports) to 1 A/cm^2. The reason for this reduction is our novel use of a nanotube-based cold cathode in a cylindrical geometry with a radius on the order of 200 microns. We believe this to be the first time this has been attempted.

Table I

Vanes n	Va (kV)	B (T)	Rc (microns)	Ra	Adjacent Vane Separatio (microns)	/ane widt /3 Spacin (microns)	Approx. Anode Field (MV/m)	mA	mW	VB/VA	v/vB(Ra-Rc
Sample 94 GHZ Magnetron choices											
Assumptions common to every case: Jo = 1 A/cm2 and efficiency = 1%											
As proposed at kickoff meeting (with Jo = 5 A/cm2):											
36	1.05	1.8	225	325	56.8	18.9	11.8	56	592	0.19	7.2
Reduce the number of vanes to 26 to increase the cavity size (note the voltage variation)											
26	2.7	1.8	250	423	102.2	34.1	17.3	13	350	0.19	7.6
26	2.19	1.8	225	381	92	30.7	15.5	11	240	0.19	7.6
26	1.73	1.8	200	338	81.8	27.3	13.8	10	170	0.19	7.6
26	1.33	1.8	175	297	71.7	23.9	12.1	9	120	0.19	7.6
26	0.98	1.8	150	254	61.4	20.5	10.4	8	75	0.19	7.6
Repeat series with slighly larger magnetic field											
26	2.78	2	250	409	98.8	32.9	19.3	13	350	0.18	7.1
26	2.25	2	225	368	88.9	29.6	17.3	11	250	0.18	7.1
26	1.78	2	200	327	79	26.3	15.4	10	175	0.18	7.1
26	1.36	2	175	286	69.2	23.1	13.5	9	120	0.18	7.1
26	1	2	150	245	59.3	19.8	11.6	8	80	0.18	7.1

In order to avoid a too high a value of anode voltage and yet to keep the device from being to small, a reasonable set of parameters appears to be the highlighted one at 2.0 T and a cathode radius of 200 microns

As indicated earlier, during this project we built a unique permanent magnet based on an 8-piece, magnetized segment, rare-earth permanent magnet design (see Fig. 5). Simulations performed in PERMAG for the Nd-Fe-B material grade N48 (nominal Br= 1.4 T) material showed that the final magnet assembly should exceed our design requirement for a total of 2 T at the center region The individual units are highly magnetized with their magnetic domains being shifted 45 degrees from one another. As a result they have a very strong repulsion of one another.

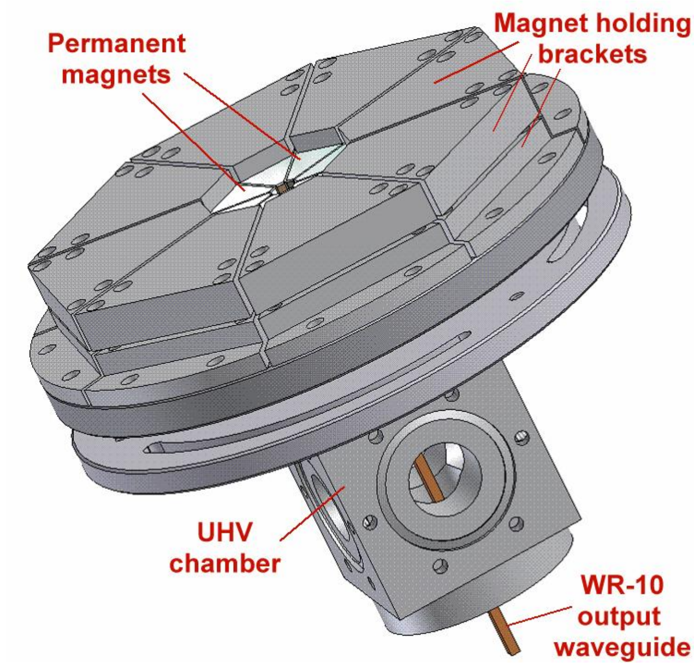


Figure 5: Magnetic assembly showing the permanent magnet holding brackets.

Pictures of a single magnet slice with its holding brackets are shown in Fig. 6. Each slice has a pair of holding brackets. Each slice-bracket assembly, in turn, is bolted down onto a holding plate as shown in Fig. 7.

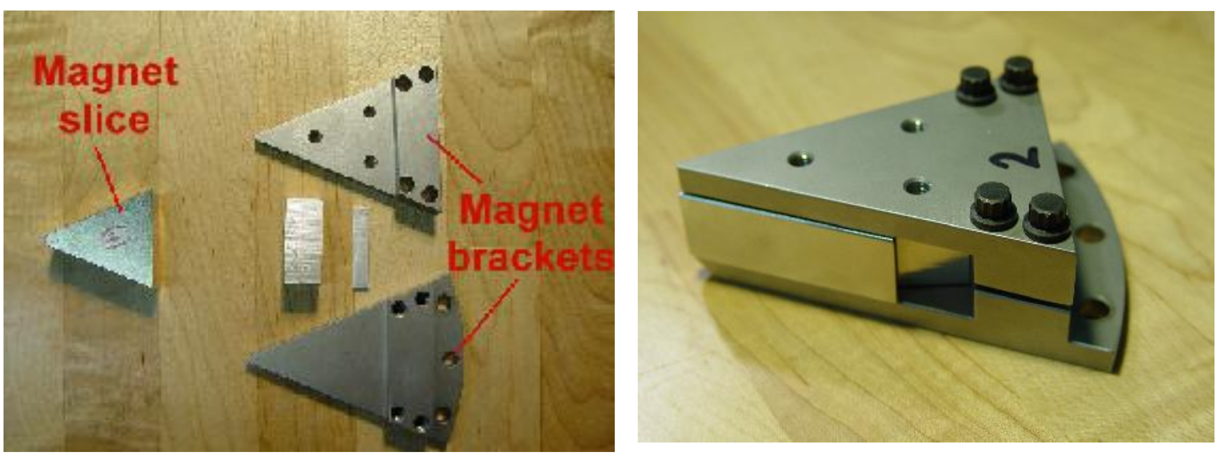


Figure 6: A single magnet slice is shown with its corresponding holding brackets.

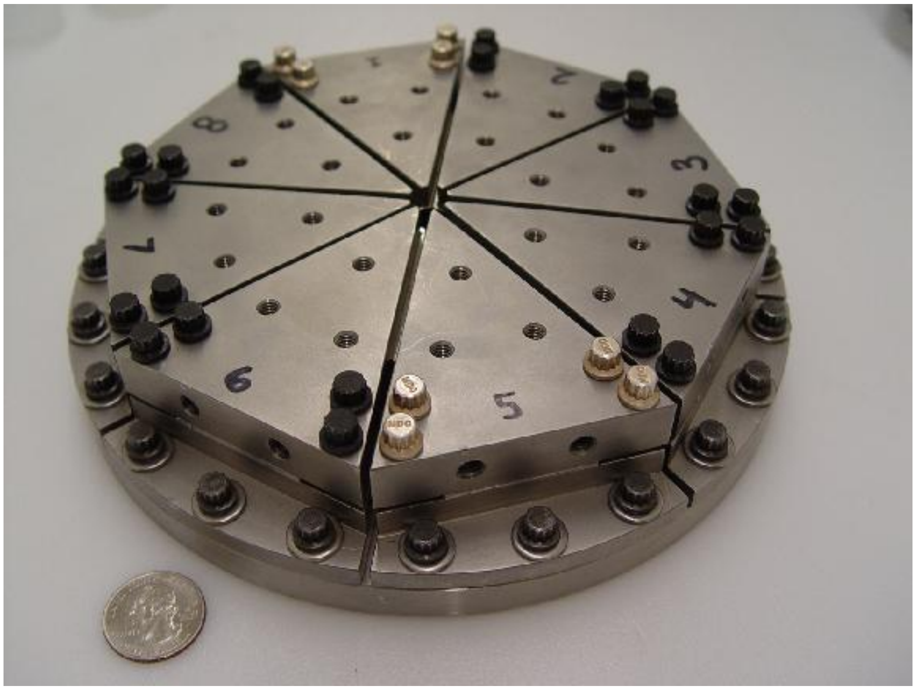


Figure 7: Entire magnet rig showing the 8 magnet slices and their corresponding brackets bolted to the main plate.

In Fig. 8 one can observe the entire test apparatus for performing the magnetic field testing of the magnet assembly. A gaussmeter in conjunction with a precision automated z-translator are used to map the transverse magnetic field produced by the magnet assembly along its axis.

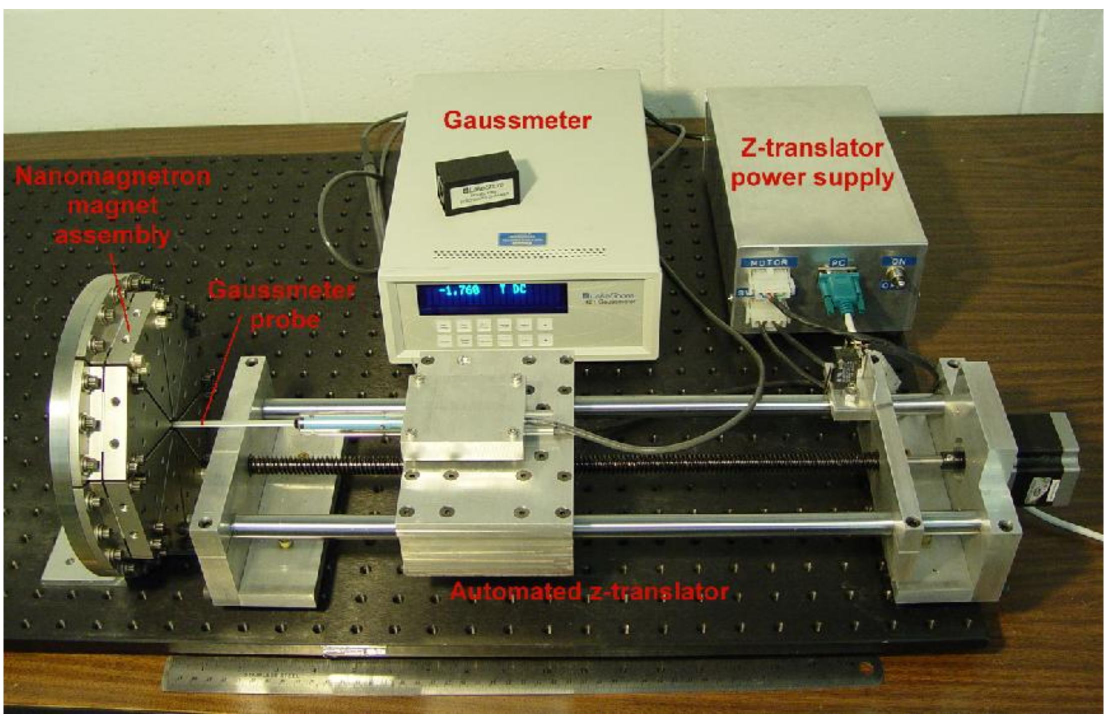
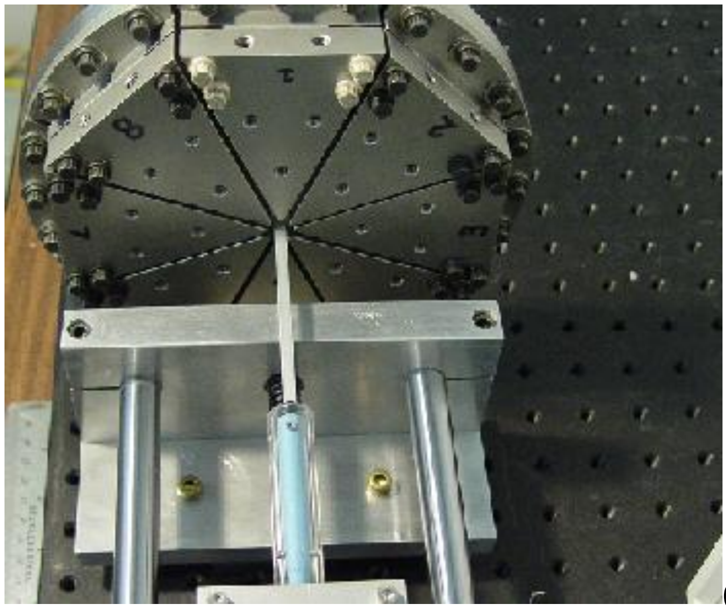
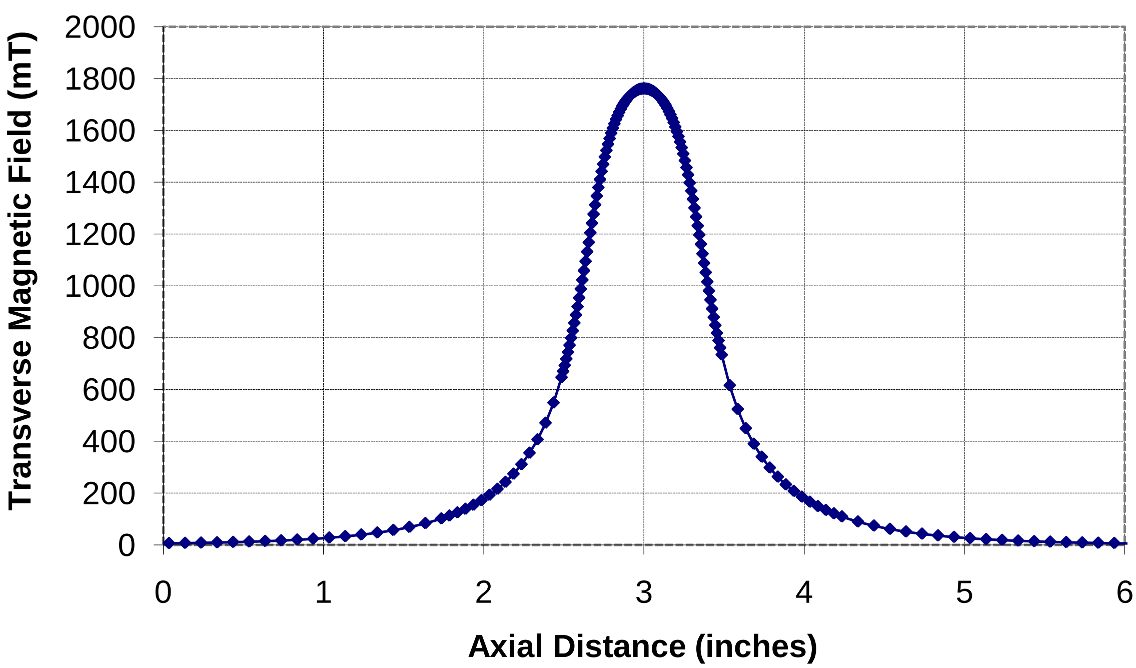


Figure 8: Experimental apparatus used to perform B-field measurements of the nanomagnetron magnet assembly.

During testing of the magnet assembly, the gaussmeter probe was placed along the axis of the magnet assembly (as shown in Fig. 9a) and was precisely moved in small steps using the automated translator. The resulting measured magnetic field along the axis of the magnet assembly is shown in Fig. 9b. Note that the B-field at the center of the magnet (z=3 in.), is very uniform, reaching a maximum value of ~1.8 Tesla. We believed this high magnetic field value to be sufficient for successful nanomagnetron operation.



(a)



(b)

Figure 9: (a) Picture of Gaussmeter probe placed along the axis of magnets assembly and (b) Magnetic field measured along the axis of the magnet assembly.

A key portion of this project was dedicated to the fabrication of magnetron parts and components required for experimental testing of the cylindrical miniature field-emission cathode, as well as to the improvement of cavity structure fabrication.

The miniature field emission cathode has a cylindrical active area of 1 mm^2 (0.4 mm diameter, 0.8 mm length). The emitter material is based on carbon nanotubes (CNTs) that are deposited onto the cylindrical substrate surface via a specialized CVD (chemical vapor deposition) process. The substrate was designed such that a) the length of the electron-emitting ring section matches the height of the cavity vanes (0.8 mm), and b) the anode-cathode separation (0.1 mm) will help provide the highest-possible electrical field strength inside the magnetron cavity.

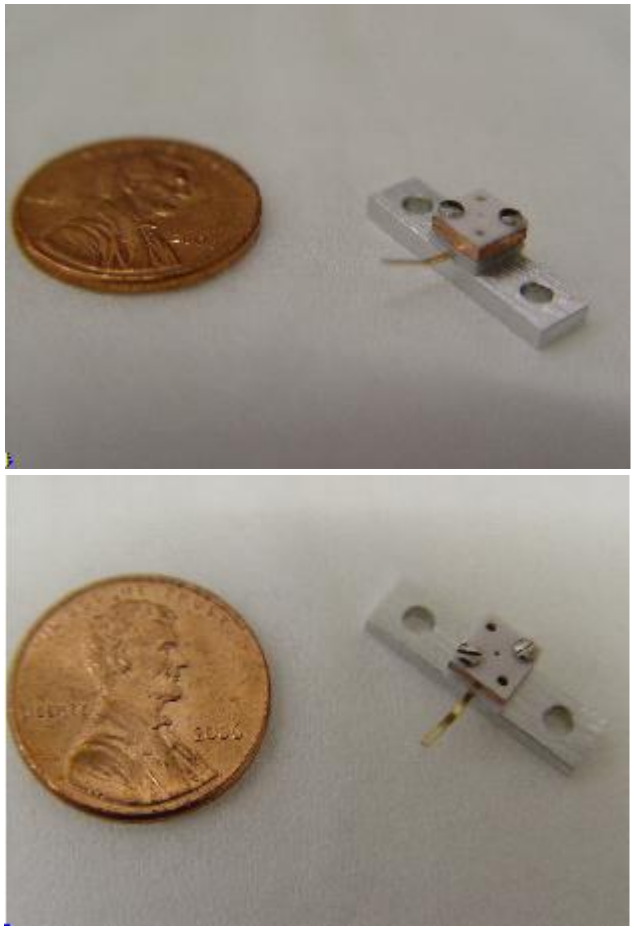
At the later stages of this project, four micro-machined cathode substrates were custom-fabricated from OFHC Copper by the company Minimatics, Inc. (Mountain View, CA). While other substrate materials, such as stainless steel or molybdenum, were possible, we chose OFHC Cu for prototype fabrication to ensure high thermal conductivity, low magnetic susceptibility, as well as standard machinability. Figure 10 shows one of the micro-machined cylindrical substrates viewed with an optical microscope before CNT deposition. Subsequently, we forwarded two of the cylindrical substrates to the company Xintek, Inc. (Durham, NC) for surface deposition of the CNT cathode layer. Figure 11 shows the completed miniature CNT cathodes (including the nanotube emitting surface).

Figure 10: Micro-machined cylindrical cathode substrate viewed with an optical microscope before CNT deposition.

Figure 11: Two fabricated miniature CNT cathodes (center). The cylindrical emission surface appears black. For size comparison, the curved edge of a 1-cent coin is visible in the upper-right corner.

In order to enable experimental testing of this novel type of cathode, the design of the magnetron cavity assembly was suitably adapted. While all dielectric components of the cavity assembly could be retained without modification, a cylindrical anode collector ring of 0.65 mm inner diameter, i.e. identical to the cavity ID, was incorporated to replace those component layers that are part of the cavity structure (cf. Figure 2 of previous progress report).

As required for the cathode assembly, the three dielectric components (0.46 mm thickness) were micro-fabricated from Macor by the company Ferro-Ceramic Grinding, Inc. (Wakefield, MA), and the metal components were machined locally by JSK, Inc. (Lorton, VA). Figures 12a and 12b show the resulting miniature assembly for cathode testing.



(a)

(b)

Figure 12: Views of the miniature assembly for cathode testing constructed from micro-fabricated components.

The development of the SU-8 lithography process for cavity fabrication by our collaborators at the University of Virginia has been ongoing during this Phase II project. Substantial progress toward the fabrication of a complete 'rising sun' cavity was made during the last 6 months of this project.

SU-8 is an epoxy-type, near-UV photoresist that has been specifically developed for ultra-thick, high-aspect ratio MEMS-type applications. Due to its excellent coating, planarization, and processing properties, as well as its mechanical and chemical stability, SU-8 has become the favorite photoresist for high-aspect ratio and 3-dimensional lithographic patterning. The SU-8 photoresist can be as thick as 2 mm, and aspect ratios >20 have been demonstrated with standard lithography equipment.

In the course of this Phase II project, process development at UVa has resulted in the successful fabrication of metalized 'rising sun' cavity structures from SU-8. During early-stage iterations, samples were fabricated as non-metalized components of different thickness, i.e. vane height. Figure 13 shows the electron microscope picture of a 'rising sun' structure fabricated with a vane height of approximately 0.52 mm.

Subsequent fabrication efforts focused on the additional metallization required to produce a highly conductive surface inside the narrow (50 to 120 micron) vane openings. Figure 14 shows the electron microscope picture of a successfully metalized 'rising sun' cavity structure. Toward the end of this reporting period, the developed SU-8 process is being tested for reliability, as well as adaptability to modified cavity dimensions.

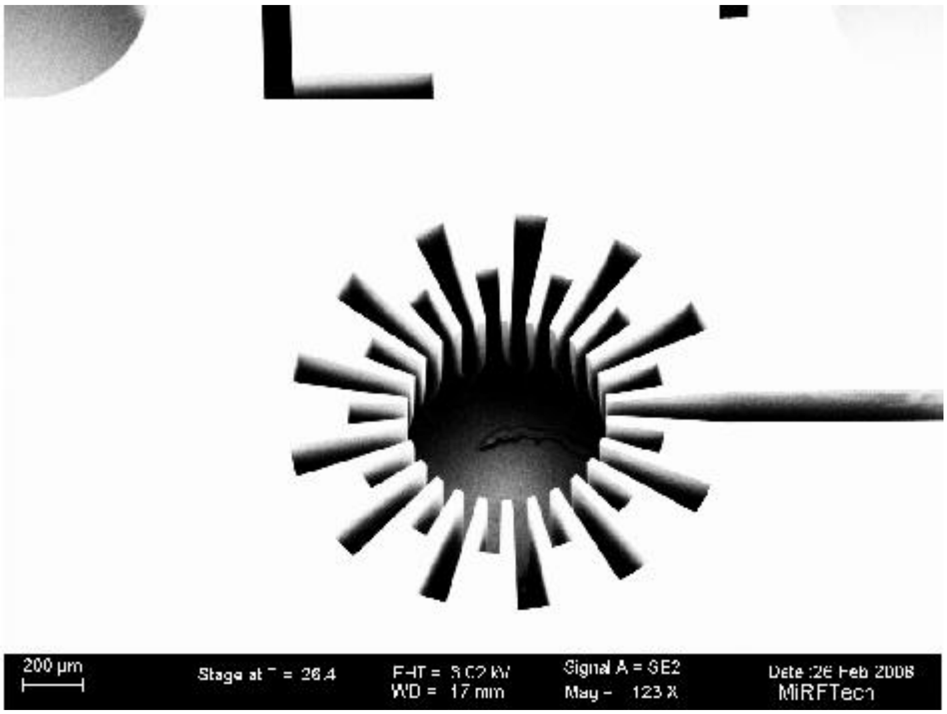


Figure 13: Electron microscope picture of a non-metalized 'rising sun' cavity structure.

As shown in the previous paragraphs, during this Phase II project we aggressively pursued the development of our novel Nanomagnetron source using theoretical, numerical and experimental studies. The main subsystems of this source were designed and built. We fabricated a permanent magnet capable of producing a magnetic field with an intensity of up to 1.8 T. In addition, a complete nanotube cathode was also complete. Finally, a miniature rising-sun cavity capable of operating at 94 Ghz was also designed and successfully fabricated using pioneering microfabrication techniques. Due to limitations in time and funding we were unable to perform testing of the complete system.

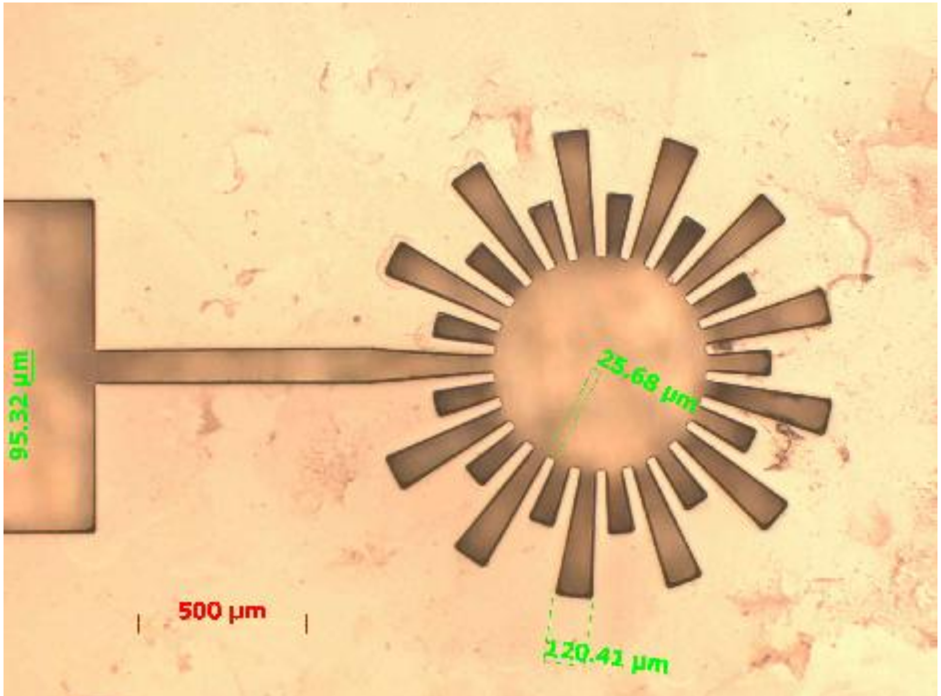


Figure 14: Electron microscope picture of a metalized 'rising sun' cavity structure.

References

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