MAGNETRONS AS SRF SOURCES*

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Abstract

Magnetrons are the lowest cost microwave source in dollars/kW, and they have the highest efficiency (typically greater than 85%). However, the frequency stability and phase stability of magnetrons are not adequate when used as power sources for accelerators. Novel variable frequency cavity techniques are being developed to phase and frequency lock the magnetrons, allowing their use for either individual cavities, or cavity strings. Ferrite or YIG (Yttrium Iron Garnet) materials are placed in the regions of high magnetic field of radial-vaned, π−mode structures of a selected ordinary magnetron. A variable external magnetic field that is orthogonal to the magnetic RF field of the magnetron is used to vary the permeability of the ferrite or YIG material in each of the π−mode structures.

INTRODUCTION

Typically, high power sources for accelerator applications are multi-megawatt microwave tubes that may be combined together to form ultra-high-power localized power stations. The RF power is then distributed to multiple strings of cavities through high power waveguide systems which are problematic in terms of expense, efficiency, and reliability. Magnetrons are the lowest cost microwave source in dollars/kW, and they have the highest efficiency (typically greater than 85%). However, the frequency stability and phase stability of magnetrons are not adequate when used as power sources for accelerators. Many systems have been developed to stabilize the magnetron frequency and phase, and patents have been developed around various techniques. Some techniques employ high-Q cavities [1, 2], and others use active devices such as PIN diodes [3] in output waveguide structures. But these techniques tend to be power limiting and produce lowered efficiencies because of added losses. External feedback circuits have been done with phase locking [4] and injection locking with some good results. In fact, there have been some reports of being able to stabilize the magnetron with a feedback loop, such that, in effect a 30 db gain amplifier can be realized [5].

In the project described here, novel variable frequency cavity techniques are being developed under a Phase II DOE STTR grant which will be utilized to phase and frequency lock magnetrons, allowing their use for either individual cavities, or cavity strings. Ferrite or YIG (Yttrium Iron Garnet) materials will be attached in the regions of high magnetic field of radial-vaned, π−mode structures of a selected ordinary magnetron.

Our work is significantly different from all other attempts to stabilize magnetrons. We are adding material to the inside of the anode structure as shown in Figure 1, that will be able to both phase lock the magnetron as well as adjust its operating frequency with a feedback loop controlling DC magnetic fields at the YIG rods.

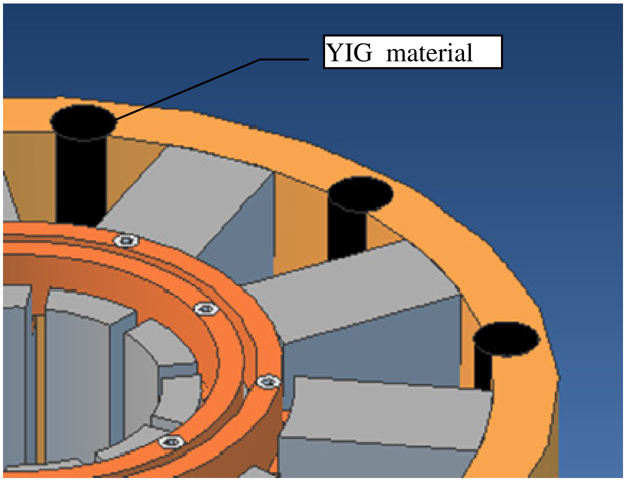

Figure 1: Schematic drawing of the strapped anode structure showing the location of the YIG rods.

TECHNICAL APPROACH

A test fixture was built as shown in Figure 2. After several attempts to design a system for attaching the material to the outer wall, a very simple design was incorporated. Instead of rectangular pieces that would need to be brazed or soldered to the outer wall, a rod was designed such that the rod was captured into the wall, and one third of the rod extended into the cell as shown in Figures 1 and 2.

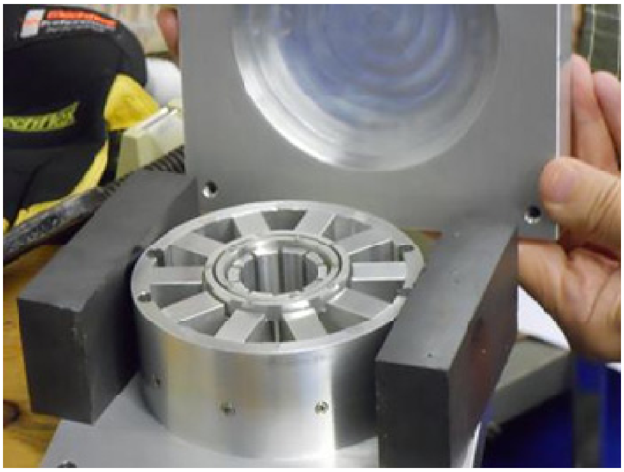

Figure 2: Test Fixture with YIG materials and permanent magnets used for tests.

Calculations and Measurements without YIG

A 3D model was made in COMSOL and the results of the calculations and measurements are shown in Table I. The measured results compare very well to the

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calculations. The errors can usually be attributed to the standard problems found in construction of a test fixture where the surfaces of the assembly pieces do not quite touch, and in the model where two mechanical surfaces are treated as one.

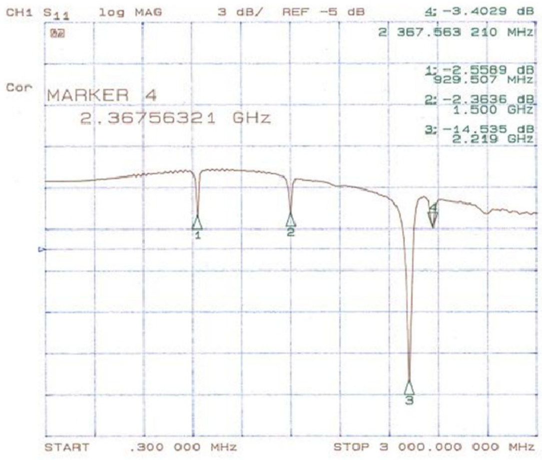

Figure 3: Frequency sweep of the test fixture without the ferrites or YIG.

Table I: Calculated and measured values of the test fixture. The TM010* is the mode in the coupling cavity shown as the cylindrical cutout in the lid in Figure 2.

Phase Shift per Cell	Calculated (MHz)	Measured (MHz)
ζ	906	935.6
ζ 5. 6ε	1496	1500
ζ 006ε	2294	2219
ζ 196ε	2872	2367

YIG and Ferrite Material Characterization

We did not perform individual measurements of the materials we experimented with other than as we used them in the test fixture. In Figure 4 we show an example of yttrium garnet characteristics from studies done with a DC magnetic field orthogonal to the RF fields [6].

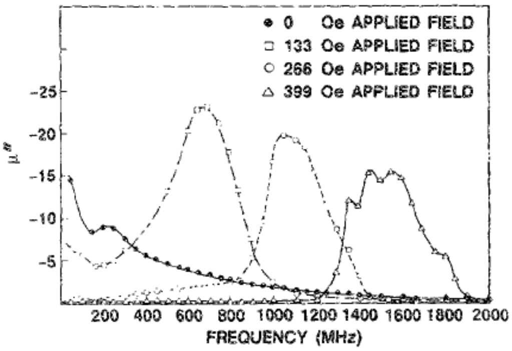

Figure 4: Im(μ) for $Y_3Al_{.66}Fe_{4.34}O_{12}$ yttrium aluminum garnet [6].

The yttrium garnets have a frequency-sensitive maximum loss that can be tuned based upon the amount of DC magnetic field. It is this loss characteristic we will use in an optimal configuration to dampen the higher order modes of the magnetron. The other characteristic of garnets and ferrites is the fact that at frequencies below the peak in loss, the frequency sensitivity of the real part of the permeability is quite different. At the low frequencies the permeability is directly proportional to magnetic field, going down as the magnetic field increases, and above the peak in loss there is no frequency sensitivity. This characteristic is shown in Figure 5 for a ferrite. Again, the magnetic field is orthogonal to the RF magnetic field.

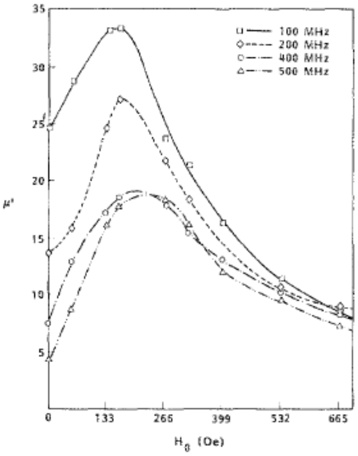

Figure 5: Re(μ) for $Mg_{.35}Zn_{.65}Fe_2O_4$ magnesium-zinc spinel ferrite [6].

For these studies, the material was yttrium-iron-garnet which has a higher saturization than the yttrium-aluminum-garnet shown in the example data of Figure 4.

Calculations and Measurements with YIG

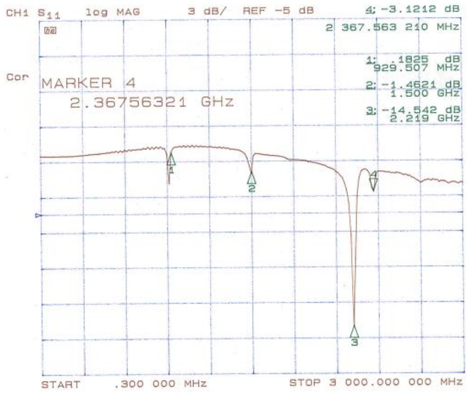

Figure 6: Frequency sweep with two YIG rods with a magnetic field 53% of the YIG saturization magnetization.

With two rods inserted in opposite cells the π-mode frequency change was 12.2 MHz resulting from an applied DC magnetic field of 950 gauss. From Figure 5 one can estimate the real part of the permeability for the test above to be $\mu_r=5$. A change of 12 MHz is quite large for this frequency magnetron, where a ±5MHz tunability would greatly improve the efficiency of a phase array system.

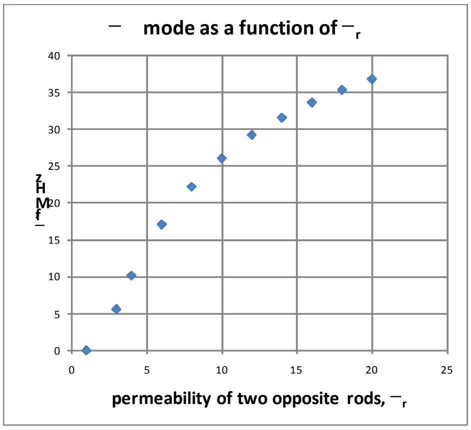

Figure 7: Calculations of the change in frequency as a function of the permeability of two rods in the anode structure.

The other thing that should be noted is how much the Q changes due to the loss in the YIG rods. Without an applied DC magnetic field, the rods are so lossy that it dampens the π-mode. With the applied field the loss decreases when operating below the resonant frequency of the YIG rods. We also see further evidence we are operating below the resonant frequency of the YIG, since the real part of the permeability decreased with increasing frequency, and the next nearest mode did not change in frequency. The implies $\mu_r \sim 1$ at the next nearest mode.

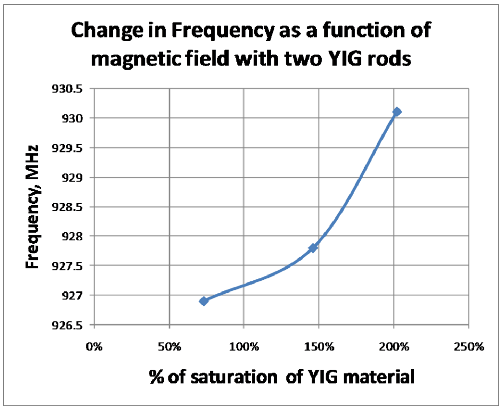

Figure 8: Change in frequency for applied DC magnetic field as a percentage of the saturization magnetization of the YIG material.

More details of the feedback circuit depend on more measurements and more experiments with the ferrite or garnet materials to be used in the cells. The block diagram shown in Figure 9 has the fundamental components necessary to perform the feedback function: The adjustable voltage source (1) is used to create a bias condition that is always on otherwise, the loss in the ferrite or garnet will attenuate any resonance. The voltage control (2) is used to adjust the locked frequency to the desired valued within the overall operating range of the device. The switch box (3) is used to control the current to the individual solenoids that control the material characteristics of one rod in one of the ten cells.

Feedback Circuit Design

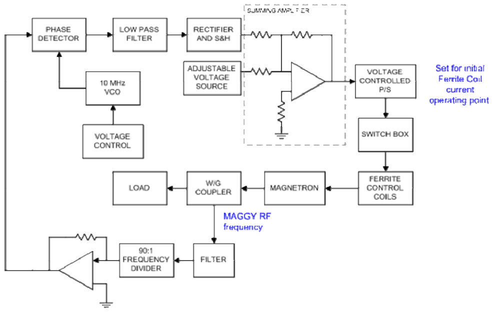

Figure 9: Feedback Circuit.

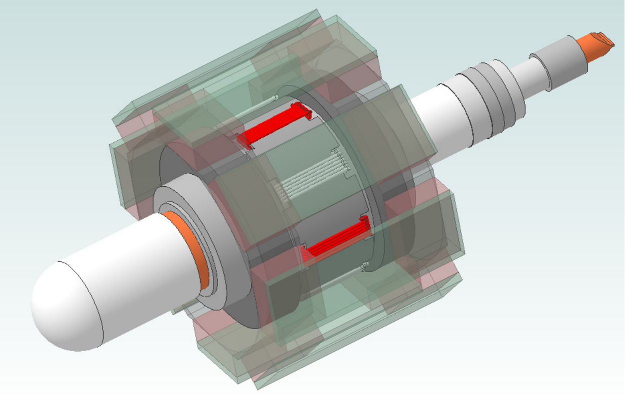

Figure 10: Conceptual picture of a magnetron showing the outer axial field magnets and the (red) coils of the transverse magnets that bias the ferrite in each π–mode structure.

CONCLUSIONS

We have demonstrated the use of yttrium garnet rods in a test fixture model of a magnetron anode. The change in frequency is as predicted for this type material and DC magnetic field. Other materials will be experimented with that require less applied magnetic field in Phase II, and a prototype tube built.

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