Microwave Journal
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www.microwavejournal.com/articles/31908-recent-advancements-in-mmwave-isolator-technology

Recent Advancements in mmWave Isolator Technology

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March 13, 2019

Isolators are non-reciprocal devices, passing electromagnetic (EM) signals in one direction and absorbing them in the reverse direction. They are primarily used to suppress standing waves that arise due to impedance mismatches between highly-tuned components, such as those found in frequency multiplier chains. Standing waves cause dips - even nulls - in the output of the multiplier chain. They can be mitigated by inserting isolators between the multipliers, resulting in a much smoother frequency response and improved bandwidth.

Traditional Faraday rotation isolators provide greater than 20 dB of isolation over full waveguide bands, with some exceeding 30 dB. While there are more than a dozen vendors worldwide, the design has largely remained static since the 1970s. Insertion loss is low in the microwave bands, steadily increasing with frequency. At mmWave frequencies, the insertion loss becomes problematic: in the WR10 band (75 to 110 GHz), insertion loss can exceed 3 dB; in the WR3.4 band (220 to 330 GHz), the loss can be greater than 7 dB, making the isolators impractical. There are few suppliers in the bands above 110 GHz; isolators for the WR4.3 and WR3.4 bands, produced many years ago, are now difficult to find. At these frequencies, the constituent parts are very small, difficult to fabricate and align - and with more than 7 dB insertion loss, there is not much demand.

In 2001, Erickson[1] demonstrated that insertion loss can be dramatically reduced. Yet, for many years following that work, very little changed in the commercial market. In 2015, with funding from NASA JPL, Micro Harmonics Corp. developed a line of mmWave isolators designed for low insertion loss. These isolators have a typical insertion loss of less than 1 dB in the WR10 band and about 2 dB in the WR3.4 band. These numbers are game changers, and mmWave system developers are reconsidering their use. Micro Harmonics is currently the only worldwide producer of full band, low loss isolators in the WR4.3 (170 to 260 GHz) and WR3.4 (220 to 330 GHz) bands, and is developing designs for the WR2.8 (265 to 400 GHz) and WR2.2 (330 to 500 GHz) bands.

FARADAY ROTATION ISOLATOR THEORY

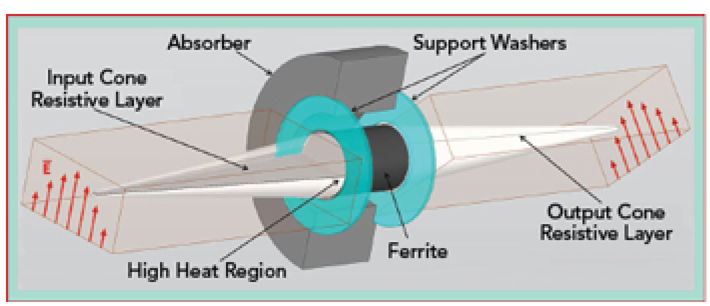


Figure 1 Structure of a Faraday rotation isolator.

At frequencies from 50 to 330 GHz, the dominant isolator topology is Faraday rotation with transitions to rectangular waveguide, as described by Barnes[2] in 1961. At the heart of the isolator are a cylindrical ferrite core and a pair of alumina cones bisected on their central axes by resistive layers (see **Figure 1**). For improved visibility, the absorber is shown split in half, with the top half of the input cone semi-transparent. The cones couple the dominant TE10 waveguide mode to the HE11 hybrid dielectric mode in the ferrite. The ferrite and cones are suspended in the waveguide structure by a pair of washer-shaped supports. The output cone and waveguide are rotated 45 degrees with respect to the input cone and waveguide. An absorber is used to suppress higher-order modes near the ferrite core.

The E-field in the TE10 mode is normal to the resistive layer in the input waveguide. The field is rotated 45 degrees counterclockwise as it passes through the ferrite and emerges normal to the resistive layer in the output cone. No currents are generated in either resistive layer by the forward traveling wave, and there is no associated loss. The direction of rotation is the same for both the forward and reverse waves, giving rise to the non-reciprocal nature of the device. The reverse traveling wave is rotated into the input cone resistive layer and absorbed, i.e., converted to heat energy.

All materials have electron spin states which create magnetic dipoles. In non-magnetic materials, the dipoles are randomly aligned, and there is no net magnetic dipole moment. In ferrite materials, some of the magnetic dipole moments can be aligned. Application of a DC magnetic bias field causes additional dipoles to align, and the magnetic moment increases. Further increases in the magnetic bias field give rise to larger net magnetic dipole moments until a point of saturation, beyond which further increases in the bias field produce no change. This condition is referred to as magnetic saturation. The magnitude of the saturation magnetization ($4\pi Ms$) is a material property in the range of 300 to 5000 G for most commercial ferrites.

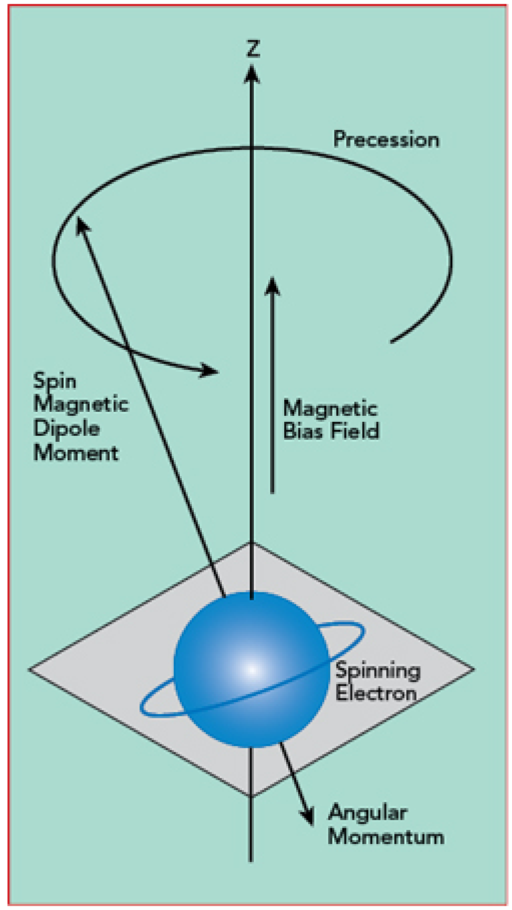


Figure 2 Spinning electron angular momentum and spin magnetic dipole moment vectors.

The magnetic dipoles precess around the magnetic bias field vector (see **Figure 2**). As an EM signal passes through the ferrite, the fields interact with the dipole moments. Linearly polarized waves, like those passing through the isolator, can be decomposed into left hand and right hand circularly polarized waves, LHCP and RHCP, respectively. The interaction with the precessing dipole moments results in disparate propagation constants for the RHCP and LHCP waves. The difference in the propagation constants is because one of the components (RHCP or LHCP) opposes the dipole precession and the other coincides. A phase shift occurs between the RHCP and LHCP waves as they travel through the ferrite, resulting in the rotation of the linearly polarized signal. A more in-depth discussion of Faraday rotation is given by Pozar,[3] Lax et al.[4] and Balanis.[5]

SIMULATIONS

HFSS6 is used to model and simulate isolator performance. The final models contain all relevant parts, including the core region surrounding the ferrite, the waveguides and twist steps. The simulations include the Faraday rotation effect using a magnetically biased ferrite, as well as ferrite dielectric loss and waveguide conductor losses.

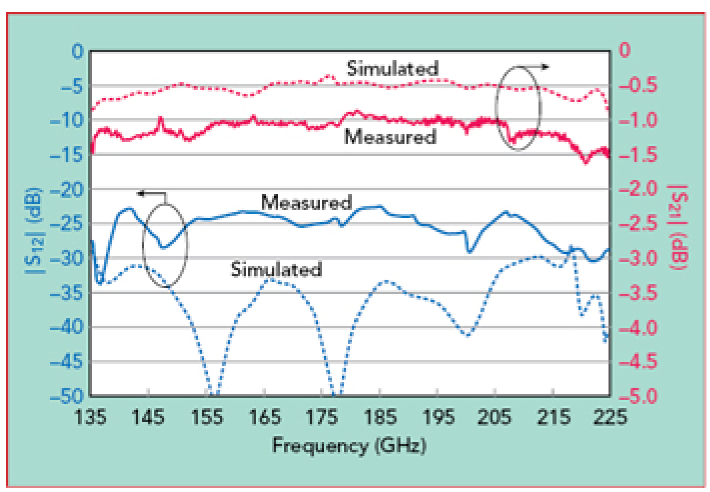


Figure 3 compares the simulation and measured data for a Micro Harmonics WR5.1 isolator. The standard WR5.1 band is from 140 to 220 GHz, and the data in the figure covers an extended range from 135 to 225 GHz. The simulated insertion loss is about 0.5 dB

lower than the measured data. The discrepancy is likely due to small misalignments in the assemblies and under-estimation of waveguide conductor loss in the models. The discrepancy between simulated and measured isolation (i.e., $|S_{12}|$) is also attributed to small alignment and fabrication errors in the constituent parts. Very little data is available on the material parameters at these frequencies, also contributing to model inaccuracies. Qualitatively, the data are in good agreement, and the measured insertion loss is much better than the typical insertion loss of old-style isolators, which was greater than 4 dB in this band.

Figure 3 Simulated vs. measured insertion loss and isolation of a WR5.1 isolator.

HFSS simulations on the WR5.1 isolator model illustrate the sensitivity to alignment and fabrication errors. Incrementally rotating the input cone out of alignment, while every other part is held in perfect alignment, degrades isolation by approximately 10 dB for a 1 degree alignment error at the center and upper end of the WR5.1 band (see **Figure 4**). A fabrication error of only ±0.001 in. in ferrite length also causes a 1 degree rotational error, with similar results.

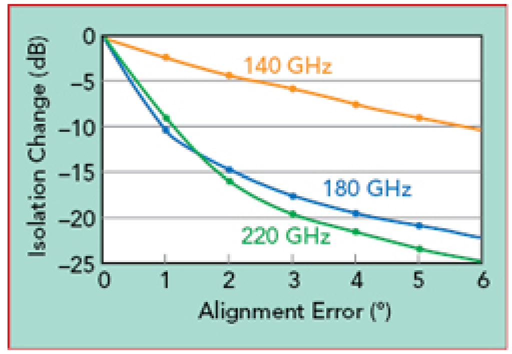


Figure 4 Isolation sensitivity to rotational misalignment of the input cone.

There are challenges to fabricating and assembling mmWave isolators. The constituent parts are tiny and, as illustrated, small alignment errors can significantly degrade performance. Misalignment can also increase coupling to higher-order modes in the region near the ferrite core, resulting in unwanted structures in the response. The assembly process is an art, and no two isolators have the same signature, motivating continual efforts to improve the uniformity of the assemblies. Every isolator is thoroughly tested on a vector network analyzer to ensure conformity with specifications.

MINIMIZING LOSS

Two of the largest contributing factors to insertion loss at mmWave frequencies are loss in the ferrite and waveguide conductor loss.

Minimizing Ferrite Loss

The EM field rotation in a Faraday rotation isolator is described by the equation

$$\theta = \frac{4\pi M_z \Upsilon l \sqrt{\varepsilon}}{2c} \qquad (1)$$

where $4\pi M_z$ is the axial magnetization, Y is the gyromagnetic ratio (8.795 x 10^6 x g rad/s/Oe), l is the ferrite length, c is the speed of light and ε is the ferrite dielectric constant. This equation shows that field rotation is directly proportional to ferrite length and axial magnetization. Minimum insertion loss and maximum isolation occur when the EM field is rotated by 45 degrees as it passes through the ferrite. Ferrites are lossy at mmWave frequencies, so it is essential that the length be reduced as much as possible.

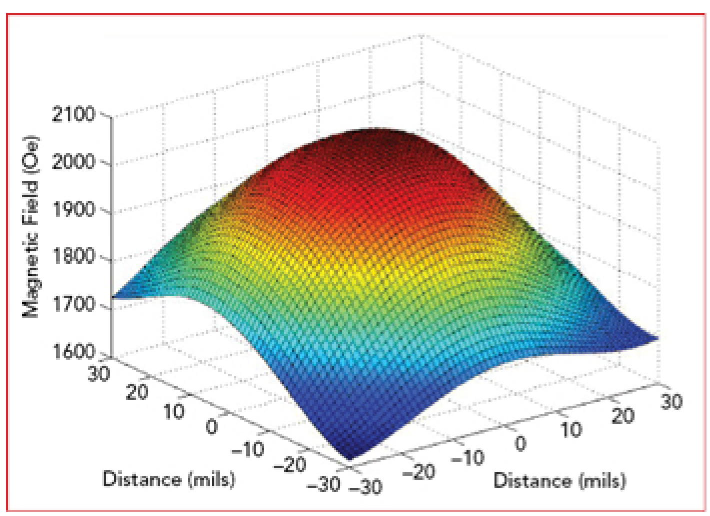


Figure 5 Measured magnetic bias field near the surface of the ferrite. The maximum field is 2056 Oe.

The traditional method to tune Faraday rotation isolators is to use ferrites substantially longer than the minimum required length and adjust the magnetic bias field to achieve a precise 45 degree rotation. This is a useful way to tune the isolator, but it comes at the cost of increased insertion loss: the ferrite is longer and unsaturated ferrites have higher loss per unit length.[3,7] In this precisely tuned state, isolators are sensitive to stray magnetic fields, which can cause under- or over-rotation of the signal. While a ferromagnetic sheath is typically employed to channel stray magnetic fields away from the ferrite, even with a sheath, there is some sensitivity.

Micro Harmonics uses a saturating magnetic bias field and the minimum possible ferrite length to yield the minimum loss in the ferrite core. The magnetic bias fields are measured to ensure ferrite saturation, and magnetic armatures are used to achieve a focused, uniform bias field in the ferrite. **Figure 5** shows the measured magnetic bias field near the surface of a ferrite. The measured peak value exceeding 2000 Oe, is substantially more than required for saturation. Only stray magnetic fields with a very strong axial component in the opposite polarity will degrade signal rotation.

Figure 6 Faraday rotation isolator with extruded waveguide twist.

Minimizing Waveguide Loss

Because the EM field is rotated by 45 degrees as it passes through the ferrite, it is necessary to realign the flanges. Traditionally, this is accomplished by twisting extruded waveguide as shown in **Figure 6**, where the twist is implemented over a sufficiently long distance to avoid damaging the extruded guide. In the WR10 through WR3.4 bands, the total length of extruded waveguide is typically more than 2 in. Micro Harmonics' designs replace the extruded twist with machined twist steps substantially shorter, which have broadband performance and reduced waveguide loss. Using this approach, the total flange-to-flange length of a WR3.4 isolator is only 0.45 in. For WR10, the reduction in waveguide loss is only 0.2 dB; however, for WR3.4, the loss reduction is close to 1 dB.

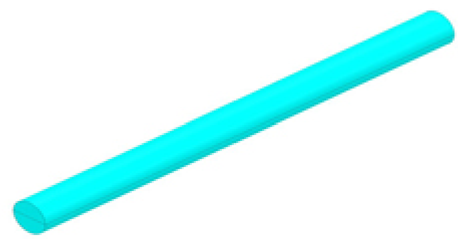
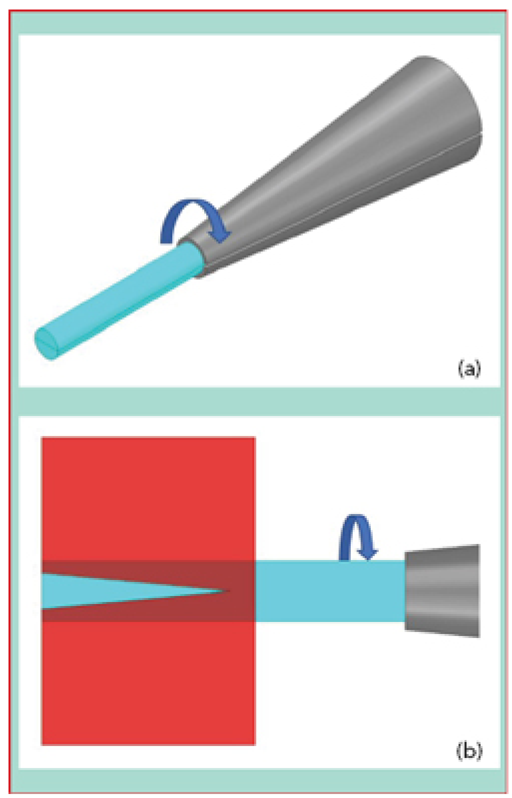


Figure 7 Cored alumina cylinder with resistive layer.

CONE FABRICATION

One of the biggest challenges at higher frequencies is fabricating the alumina cones. The traditional method begins by laminating two alumina plates together with a resistive layer at the interface. The plates are turned on their sides and cored, producing alumina cylinders with a resistive layer bisecting the central axis (see **Figure 7**). The cylinders are then ground to a cone shape. Using this approach, tip diameters less than 0.004 in. are difficult to achieve, as few machinists can fabricate the cones for WR4.3 and WR3.4 waveguide isolators - the difficulty is even greater for WR2.8 and WR2.2.



Micro Harmonics is experimenting with alternative techniques to form the smallest cones by using cold laser ablation. This approach is appealing because no pressure is applied to the alumina; the process uses no heating, which can damage the epoxy and resistive layers; and forming cones with very small tips may be feasible. The cored cylinders have two ends that are flat and orthogonal to the central axis and suitable for cone bases. The alumina cylinder is then chucked and rotated (see **Figure 8**), and as material is ablated, the cone eventually detaches from the cylinder.

Figure 8 Chucked alumina cylinder (a), rotating during cold laser ablation (b). The red area shows the exposure to the laser.

Diamond Heatsinks

In most commercial Faraday rotation isolators, the ferrite and cones are suspended by a pair of washer-shaped supports (see **Figure 9**). The cone/ferrite assembly is inserted through the inner support holes and attached with a non-conductive epoxy. The support material is typically biaxially-oriented polyethylene terephthalate (BOPET), Styrene, a resin or some other material with a low dielectric constant and low loss at mmWave frequencies. Materials with these characteristics are generally thermal insulators, thermally isolating the cones and ferrite from the metal block.

In an isolator, absorbed power from the reverse traveling wave is converted to heat energy in the input cone. Very little of this heat can be channeled away by thermal conduction through the washer-shaped supports; rather, it must be dissipated by radiation or convection through the surrounding air. If too much reverse power is incident on the device, the resistive layers are subjected to high heat levels and may be damaged. Higher power sources becoming available has renewed interest in improving the power rating of the isolator.

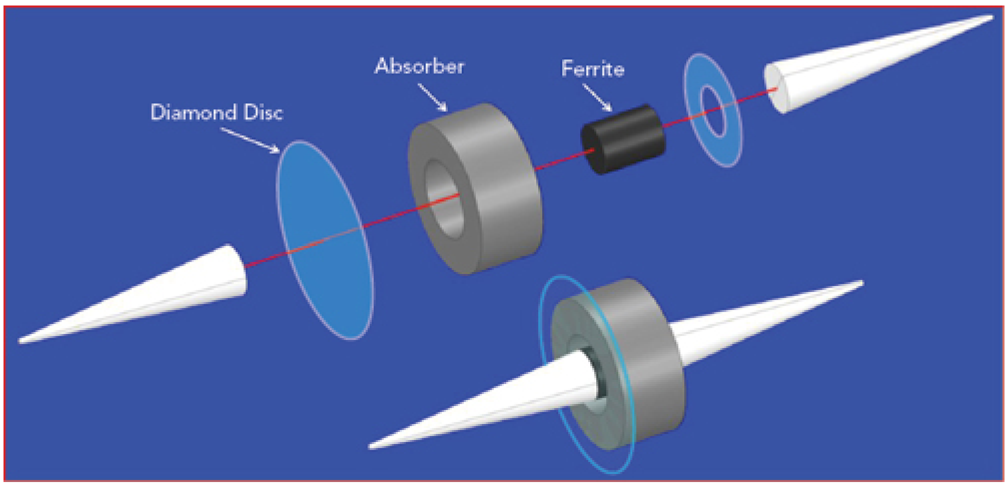


Figure 9 Exploded view showing the cones, absorber, ferrite, support washer and diamond disc.

Micro Harmonics has addressed this by replacing the input support washer with a uniform, high grade, optical chemical vapor deposition (CVD) diamond disc, shown in Figure 9. The thermal conductivity of diamond is near 2200 W/mK, more than 5x higher than copper. The diamond disc is sandwiched between the base of the input cone and the ferrite, in intimate contact over the entire area of the cone base, which is the optimal location for the diamond disc since it is the region subject to the highest heat (see **Figure 10**). The diamond disc is attached to the metal waveguide block over its entire periphery, providing an excellent conduit to channel heat from the resistive layer. The arrows in the figure illustrate the heat flow, showing this topology is superior for thermal conduction. This isolator design will handle higher reverse power levels while maintaining lower core temperatures, improving reliability.

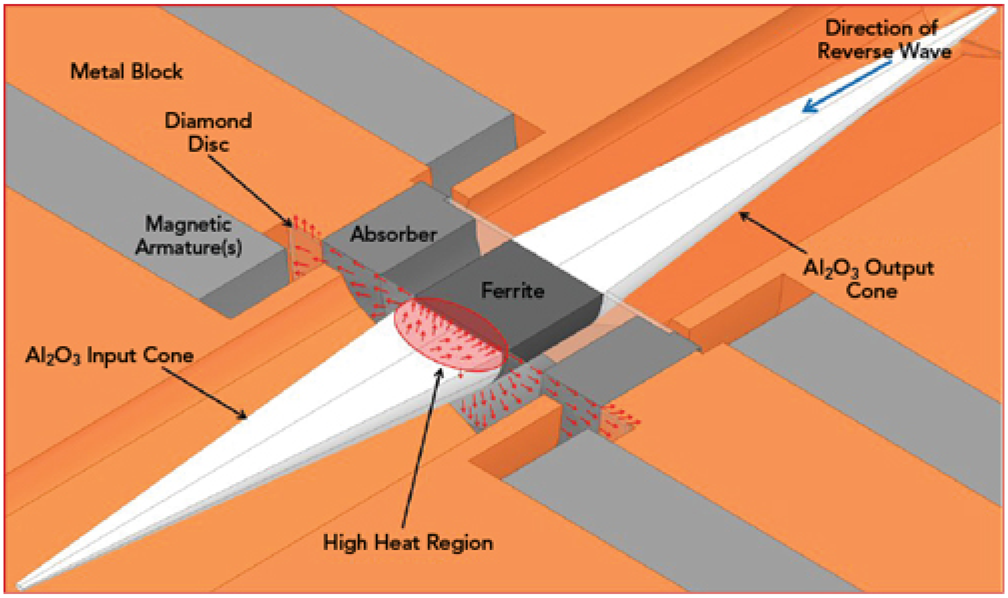


Figure 10 Thermal path through the diamond support disc.

Cryogenic Applications

NASA recently awarded Micro Harmonics a contract to develop isolators optimized for cryogenic temperatures. In addition to the low temperature thermal stress, the substantial temperature dependence of the ferrite saturation magnetization is also a challenge. The measured isolation of a WR10 isolator drops from 30 dB at 290 K to 14 dB at 77 K, caused by a 10 degree over-rotation of the EM fields from higher magnetization at 77 K.

Ferrite magnetization follows a modified Bloch law:

$$M(T) = M(0) * \left(1 - \left(\frac{T}{Tc}\right)^{\alpha}\right) \qquad (2)$$

where M(T) = magnetization, M(0) = magnetization at 0 K, T_c = Curie temperature and α = the temperature exponent. The Curie temperature is the temperature at which materials lose their permanent magnetic properties. The Bloch law typically follows an α = 3/2 form,[8] although evidence in the literature suggests that a modified Bloch law with α = 2 is a better fit for nickel spinel ferrites.[9-10] The decrease in magnetization at higher temperatures is caused by the increasing excitation of spin waves, which makes it more difficult to align the magnetic dipoles.

Fitting measured data to a modified Bloch law with M(77 K) = 6170 G, T_c = 648 K, M(0 K) = 6250 G and α = 2.07 yields the solid curve in **Figure 11**. Some literature says the magnetization can depart from the modified Bloch Law at temperatures below 50 K, depending on the ferrite particle size (the blue curve in the figure).[10]

SUMMARY

This article described a new and innovative design approach for mmWave isolators, which has been used to develop isolators for every waveguide band from WR15 through WR3.4, i.e., 50 to 330 GHz. The designs employs diamond heatsinks for improved thermal conduction and achieve typical insertion loss less than 1 dB for WR10 (75 to 110 GHz) and less than 2 dB for WR3.4 (220 to 330 GHz) - a significant improvement over the previous state-of-the-art. The same design approach is being used to develop isolators for WR2.8 (265 to 400 GHz) and WR2.2 (330 to 500 GHz). NASA is also funding development of mmWave isolators for cryogenic systems.

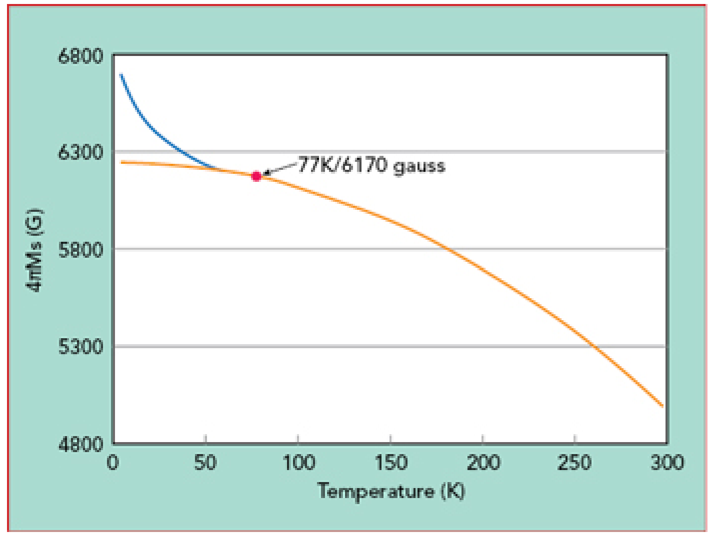


Figure 11 Temperature dependence of the saturation magnetization.

Acknowledgments

Micro Harmonics would like to thank NASA for the continued support of this work through research contracts NNX15CP37P, NNX16CP07C and 80NSSC18P2018.

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