Cryogenic Faraday Rotation Isolators

Cryogenic Components | Isolators

David W. Porterfield - Micro Harmonics Corporation
Nov 6, 2023

Faraday rotation isolators designed for room temperature operation do not work well at cryogenic temperatures. The primary cause is temperature-dependent ferrite magnetization. **Figure 1** shows measured data for a WR-10 Micro Harmonics isolator designed for room temperature operation. The isolator uses a ferrite material with a saturation magnetization of 5000 gauss [1]. The isolation is near 25-30 dB at 298 K but drops to about 14 dB when cooled to 80 K. HFSS [2] simulation data for the isolator are also shown where the ferrite magnetization is increased to 6000 gauss. More on that later.

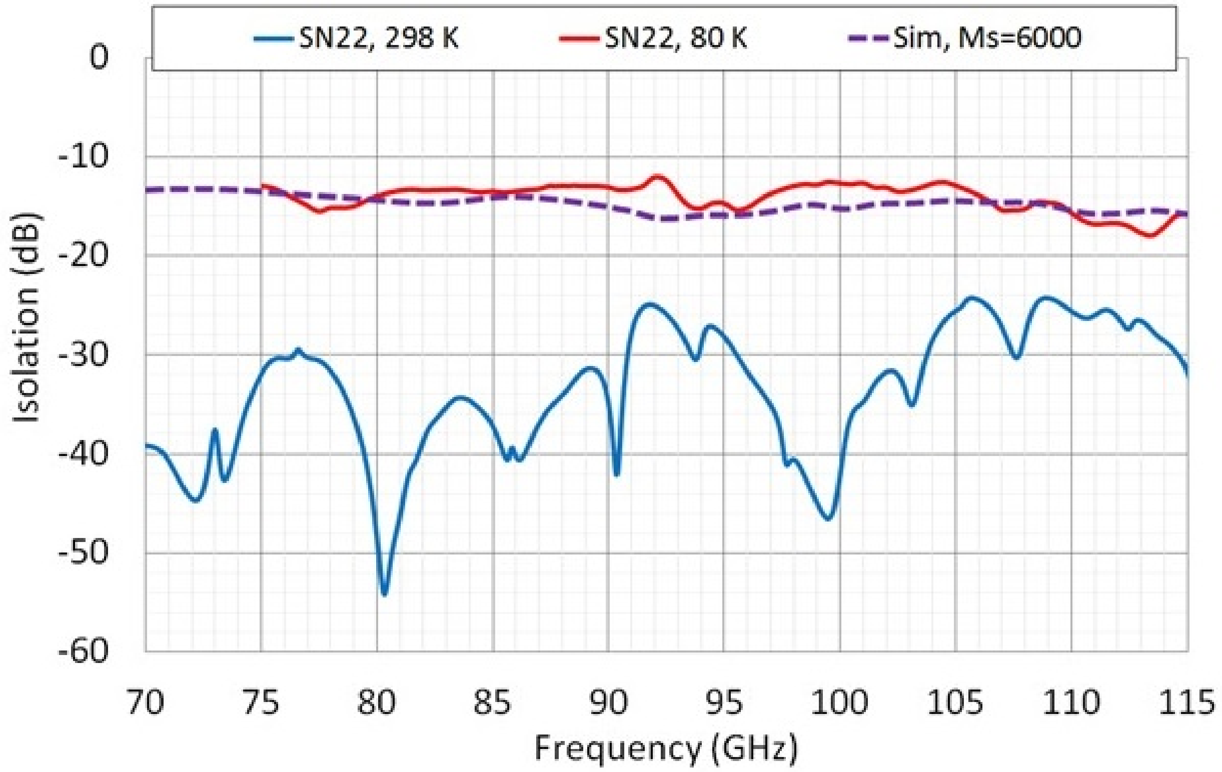


Figure 1. *Measured isolation for a WR-10 isolator (serial # 22) at 298 K and 80 K. The dashed line shows data from a simulation where the ferrite magnetization is set to 6000 gauss.*

To achieve optimal performance in a Faraday rotation isolator, the RF signal polarity must be rotated by exactly 45° as it passes through a cylindrical ferrite rod. For the forward travelling signal, 45° rotation keeps the electric field normal to the plane of an embedded resistive layer. For the reverse travelling signal, 45° rotation puts the electric field in the plane of the resistive layer yielding maximum signal loss and isolation. The equation for signal rotation in a Faraday rotation isolator is given by,

$$\theta = \frac{4\pi M_Z \Upsilon l \sqrt{\varepsilon}}{2c}$$

Where,

θ is the angle of rotation, $4\pi M_z$ is the axial magnetization, *l* is the ferrite length,

Υ is the gyromagnetic ratio ($8.795\text{x}10^6$xg rad/s/Oe), c is the speed of light,

ε is the ferrite dielectric constant.

As the axial magnetization ($4\pi M_z$) increases, the rate of signal rotation increases proportionally. There is an upper limit to the axial magnetization called saturation magnetization ($4\pi M_S$) beyond which any further increase in the magnetic bias field does not change the rate of rotation. The saturation magnetization for a given ferrite material is usually specified at room temperature.

Ferrite magnetization varies with temperature following a modified Bloch Law;

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

Where,

M(T) = Magnetization, M(0) = Magnetization at 0 K, Tc = Curie temperature

The Bloch Law typically follows an α = 3/2 form, but there is evidence in the literature to suggest that a modified Bloch Law with α =2 is a better fit to the data for nickel spinel ferrites [3, 4] such as Trans-Tech's TT2-111 [1]. The decrease in magnetization at higher temperatures is caused by the increasing excitation of spin waves which makes it more difficult to align magnetic dipoles. The Curie temperature (Tc), is the temperature above which materials lose their permanent magnetic properties.

Figure 2 is an estimate of M(T) for ferrite TT2-111 [1]. The saturation magnetization increases by about 18% when cooled to 0 K. The data are based on RF tests of Faraday rotation isolators at temperatures between 295 K and 25 K. It should be stressed that the magnetization was not measured directly but rather observed changes in the isolation were attributed to changes in the magnetization.

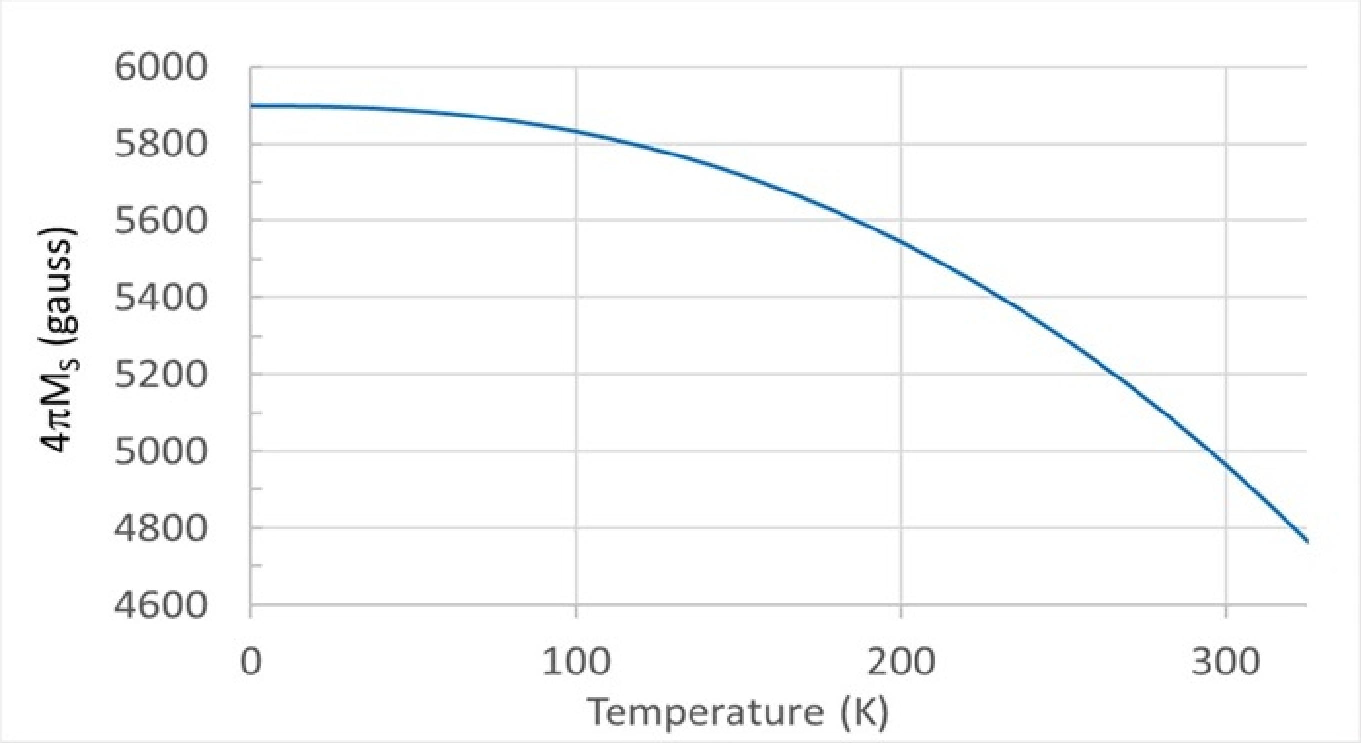
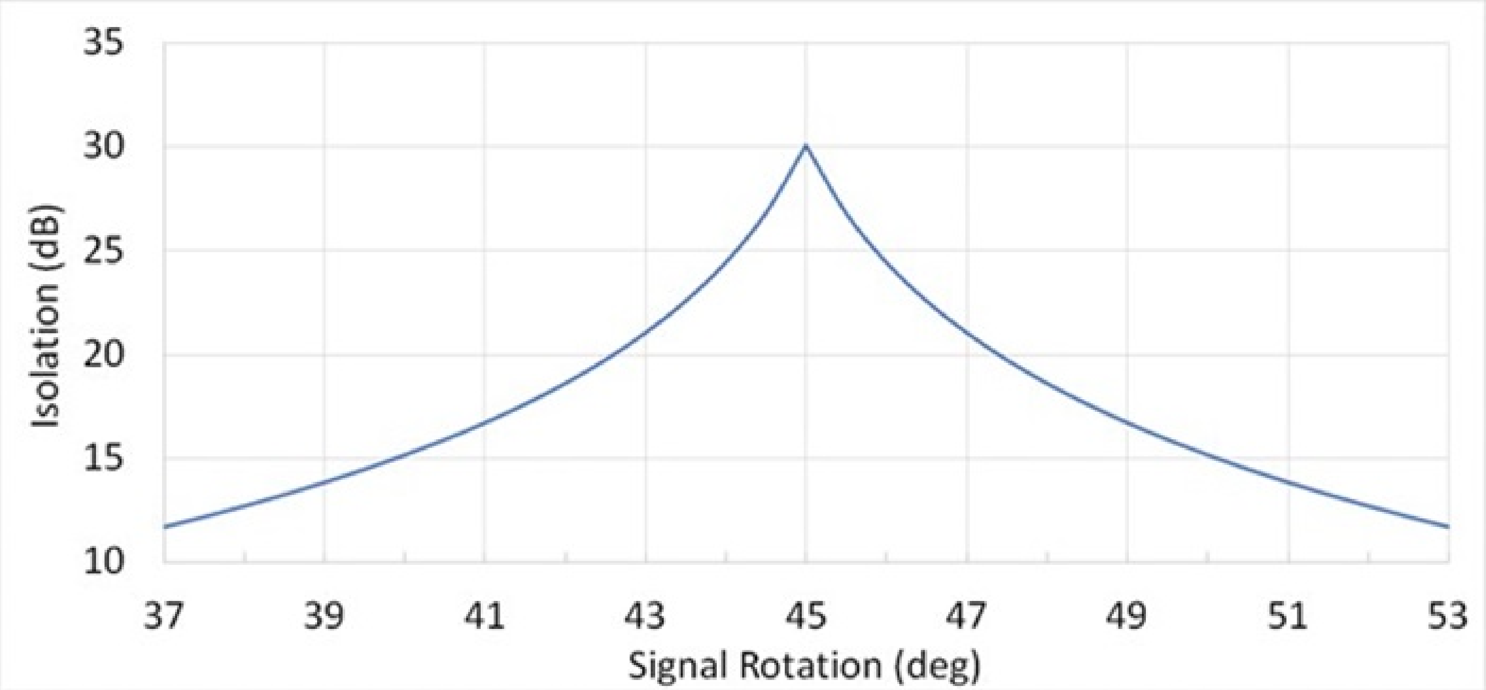


Figure 2. *Estimate of the saturation magnetization for TT2-111 as a function of temperature*

In a Faraday rotation isolator, the isolation varies as the cosecant squared of the angle as the signal is rotated out of the plane of the resistive layer. **Figure 3** shows $\csc^2(\theta - 45°)$ so that the cosecant function goes to infinity at $\theta = 45°$. Modifications are made to the function to limit the peak isolation to a realistic value of 30 dB. An increase in the rotation of 18% equates to a rotation of 53° and a drop in isolation to around 12 dB. This agrees well with the change in measured isolation shown in Figure 1. Although the data in Figures 2 and 3 are not exact, they are helpful in understanding the impact of cooling a Faraday rotation isolator to cryogenic temperatures.



Temperature Dependence of Magnets

Another consideration in the design of cryogenic Faraday rotation isolators is the temperature dependence of the permanent magnets used to bias the ferrite material[5]. Micro Harmonics uses powerful neodymium magnets to bias their room temperature isolators into magnetic saturation. They are inexpensive due to their widespread use in other industries. However, neodymium magnets lose some of their magnetic field strength as they are cooled as indicated in the graph in **Figure 4**. We use high-grade samarium cobalt (Sm_2Co_{17}) magnets in our cryogenic isolators since they are much less sensitive to temperature variations.

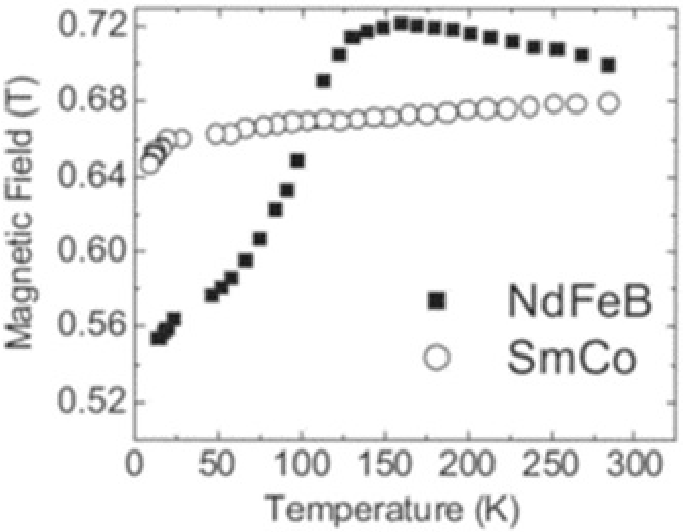


Figure 4. Temperature Dependence of NdFeB and SmCo Magnets [5]

Insertion Loss – Another important characteristic of a mm-wave isolator is insertion loss. The traditional style or “legacy” Faraday rotation isolators that have been on the commercial market for more than fifty years have high insertion loss at the higher mm-wave frequencies. **Figure 5** shows insertion loss for the legacy style isolators (lower left) in all standard waveguide bands from WR-15 (50-75 GHz) through WR-3.4 (220-330 GHz). In the WR-6.5 band (D-band), the insertion loss of a legacy isolator is more than 3 dB which means more than 50% of the forward travelling signal is lost. In the WR-3.4 band, the insertion loss of the legacy isolators is more than 8 dB with less than 15% of the signal passing in the forward direction. This level of loss is unacceptable in most systems operating at room temperature and even more intolerable in cryogenic systems where performance is at a premium.

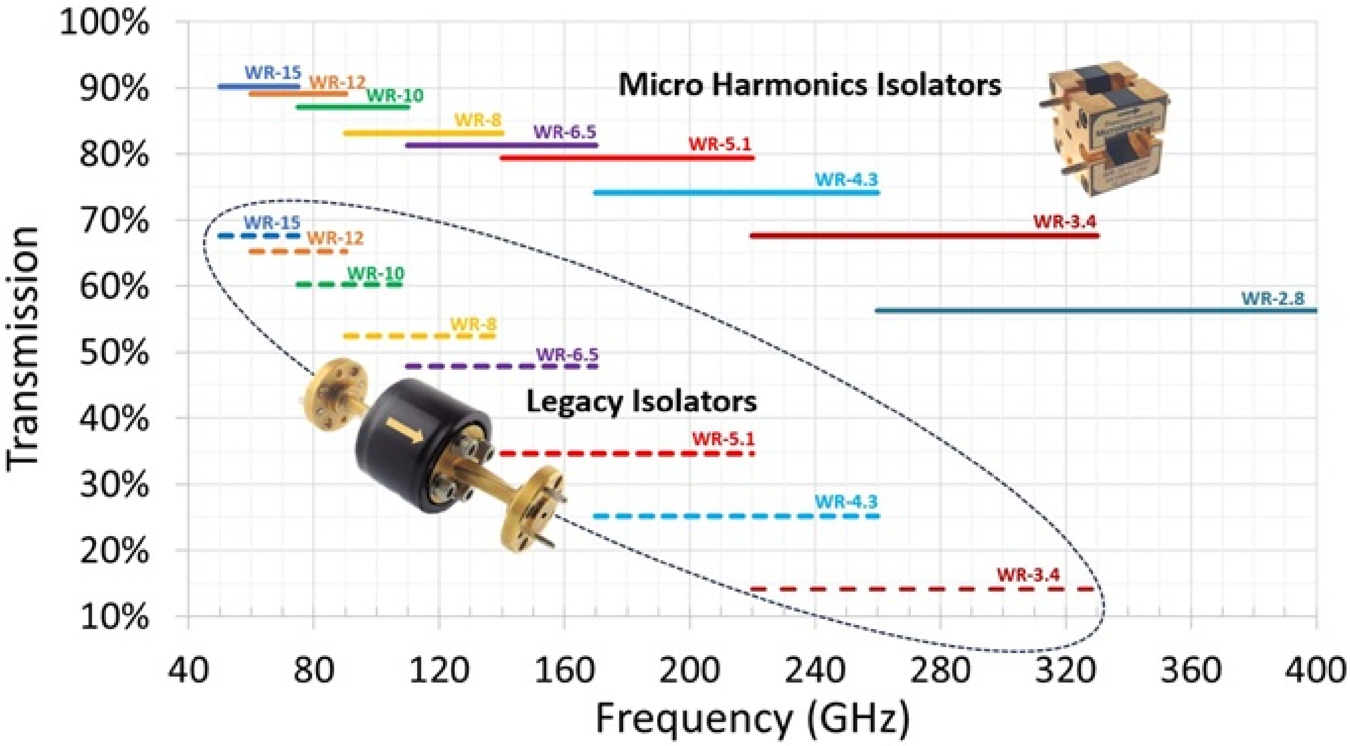


Figure 5. *Insertion loss of traditional style “legacy” isolators and Micro Harmonics isolators*

Micro Harmonics redesigned the Faraday rotation isolator by saturating the magnetic bias and reducing the ferrite rod length to the minimum possible value to achieve the required 45° rotation [6]. The insertion loss of the Micro Harmonics isolators is only 1 dB in the WR-6.5 band and less than 2 dB in the WR-3.4 band. The data in **Figure 5** are for isolators operating at room temperature. For the cryogenic isolators we were able to further reduce the ferrite length due to the higher ferrite magnetization at cryogenic temperatures (**Figure 2**). The shorter ferrite rod in conjunction with reduced ohmic losses at cryogenic temperatures leads to even lower insertion loss in the cryogenic isolators.

There are claims that some legacy-style isolators maintain reasonably good isolation at cryogenic temperatures. This might be possible due to a happy coincidence. Since the legacy isolators are not operated in saturation, the signal rotation is more sensitive to changes in the magnetic bias field. The reduction in the magnetic bias field at cryogenic temperature (**see Figure 4**) may be sufficient to partially offset the increase in the ferrite magnetization. But even if this is the case, the legacy isolators still have significantly higher insertion loss than the Micro Harmonics isolators.

Size Considerations – Size and weight are often important considerations in mm-wave systems. This is especially true for cryogenic systems due to the limited space available on a cold plate. We design our cryogenic isolators to have the smallest possible footprint on the cold plate. For example, in the WR-10 band 75-110 GHz, a Micro Harmonics isolator has external dimensions 19 x 19 x 16.7 mm and weighs only 16 grams as shown in **Figure 6**. The 19 x 19 mm cross-section is the size of a standard waveguide flange which ensures that the isolator can lay flat against the cold plate without impacting the position of other system components. A typical competitor isolator in the same WR-10 band measures 25 x 25 x 70 mm and weighs 60 grams. The difference is a factor of four in both size and weight.

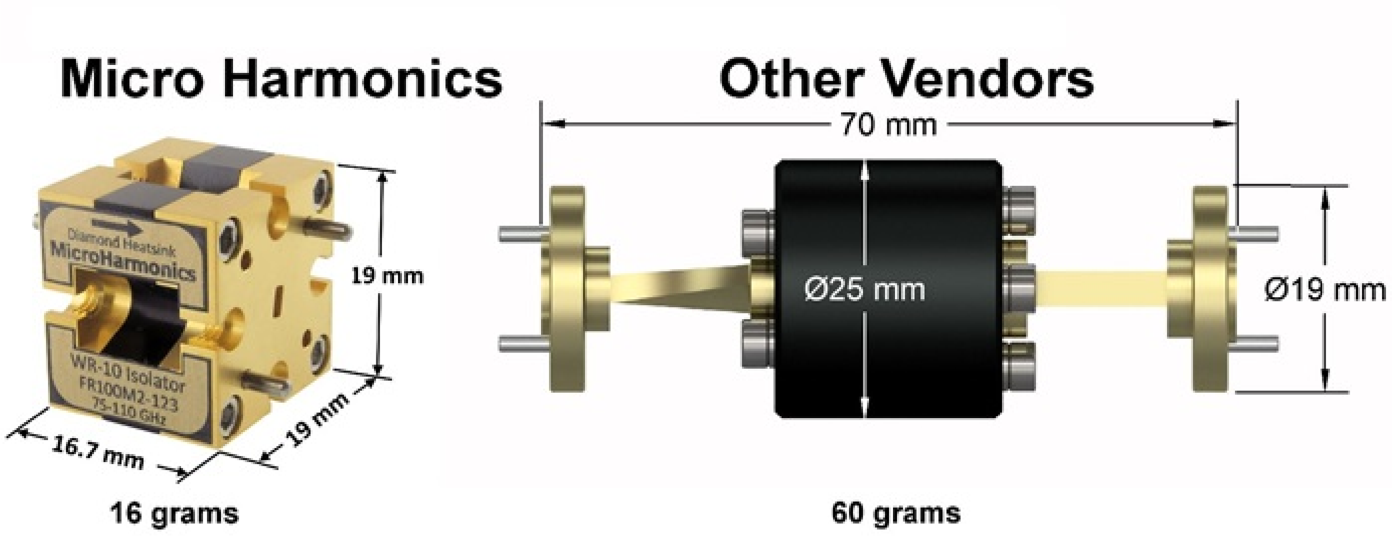


Figure 6. *Size and weight comparison of WR-10 isolators*

Thermal Stress – Cryogenic cycling creates stress in the isolator assemblies as the constituent parts contract and expand at different rates. To determine failure mechanisms and weak points in our assemblies, we perform extensive cryogenic cycling tests. The goal is to make the cryogenic isolator assemblies robust and reliable when subjected to repeated cryogenic cycling. The information obtained from these tests has proven invaluable and led to changes in the way we design and assemble our cryogenic isolators.

Our cryogenic cycling tests comprise total submersion in liquid nitrogen (LN2) at 77 K for approximately 1-2 hours followed by removal from the LN2 dewar and an additional 1-2 hours at room temperature. We wrap our isolators in a protective layer of foam and enclose them in vacuum-sealed bags to prevent condensation. The isolators are inspected periodically for physical damage such as delamination at epoxy joints and cracks in dielectric materials. They are also periodically RF tested to ensure that there are no changes in performance.

The initial cryogenic cycling was done on a series of isolators employing CVD diamond support discs. The diamond is used in our standard isolators to channel heat from the resistive layer to the metal waveguide block. This allows our isolators to handle significantly higher power levels than competing products. Isolators with the CVD discs survived for more than 100 cycles with no failures detected. They were removed from the cycle so that other configurations could be examined. Although there were no failures detected, thermal stress simulations indicated high stress levels in the diamond disc caused by the severe mismatch in the coefficients of thermal expansion of the diamond and the aluminum block.

Subsequently, some isolator assemblies were tested without cones or ferrite rods attached to the CVD diamond. The diamond was attached on its periphery either to the RF absorber or to the metal block. The diamond discs in these assemblies failed after only a few cycles. A typical diamond disc failure is shown in **Figure 7**. It is thought that the ferrite and cones provide extra support in the center of the disc which kept the diamond from buckling and breaking under the stress imparted by the aluminum block.

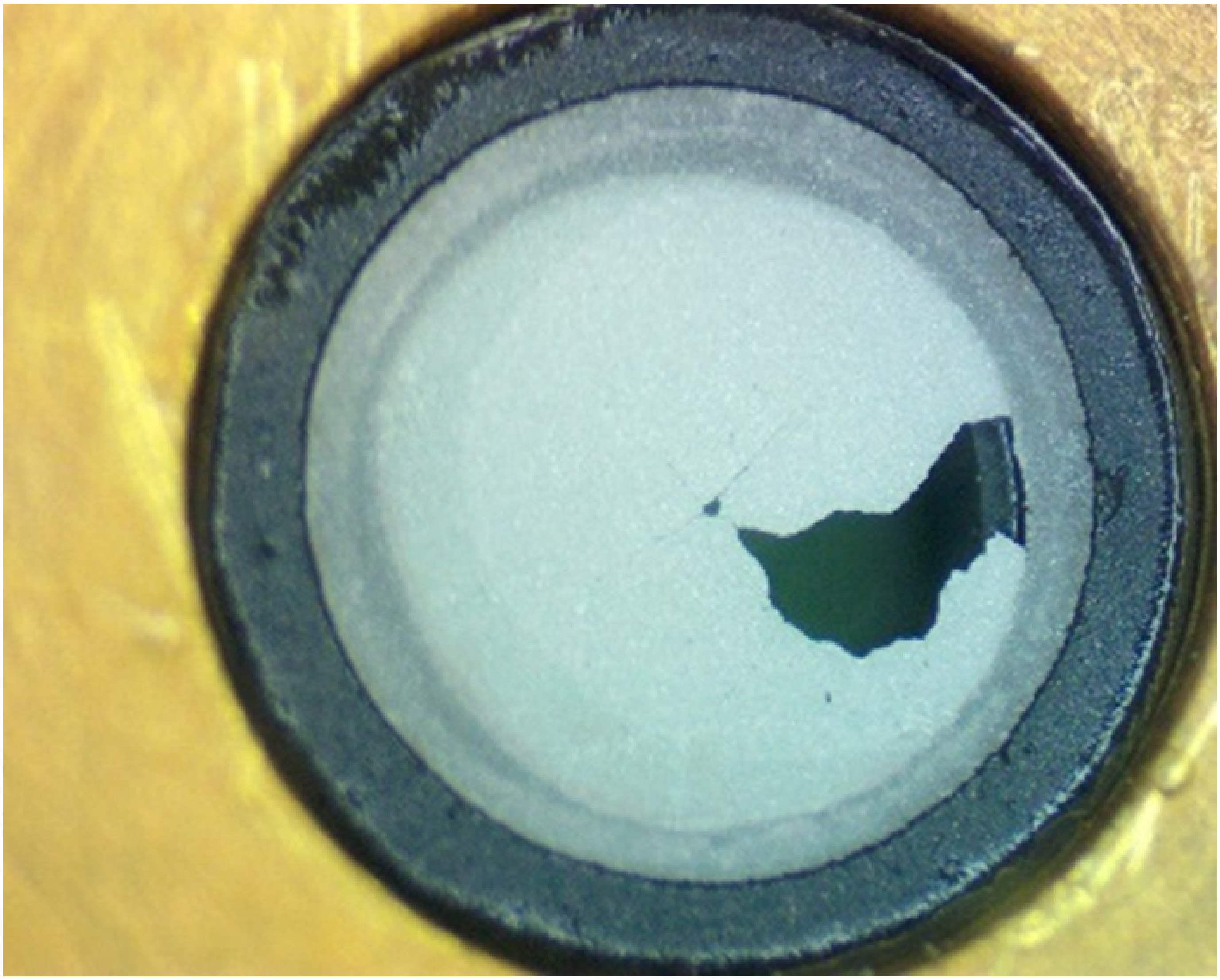


Figure 7. *Broken CVD diamond disc (white). The diamond is attached to the RF absorber (black). There were no ferrite or cones in the assembly. The failure occurred after three cryogenic cycles.*

Both the cryogenic cycling tests and the thermal stress simulations indicated that the CVD diamond discs were under severe stress at cryogenic temperatures. We changed our standard cryogenic assembly, removing the CVD diamond disc and replacing it with another, more pliable material. The new standard ensures that the isolators can withstand the mechanical stresses incurred during repeated cryogenic cycling. **Table 1** shows a summary of the cryogenic cycling data for five isolators tested in the period from 2016 to 2018. During that time, no detachments nor any other defective conditions were observed. RF tests confirmed there was no degradation in performance in any of the isolators.

Cryogenic Isolator Test Data – We design our cryogenic isolators to have optimal performance at a temperature near 130 K. This yields very good performance at the lower cryogenic temperatures where the signals are only slightly over-rotated while maintaining a reasonable level of performance at room temperature where the signals are under-rotated. This is done so that the isolators work reasonably well at room temperature which enables cryogenic systems to be evaluated at room temperature during the R&D and prototyping stage. We test every cryogenic isolator that we make both at room temperature and at cryogenic temperature, typically 25 K. We do not perform cryogenic cycling tests on the isolators that we sell but rely on historical cycling data and rigorous assembly standards.

Figure 8 shows the measured isolation and insertion loss at both room temperature (300 K) and cryogenic temperature (25 K) for one of our WR-10 cryogenic isolators. Data are shown over the extended band from 70 GHz to 115 GHz. Insertion loss at room temperature is less than 1.2 dB across the tested band and less than 0.6 dB in the band 73-107 GHz. The insertion loss at 25 K improves to a maximum of 1 dB from 70-115 GHz and less than 0.4 dB in the band 73-110 GHz. The isolation is greater than 15 dB in the band 70-115 GHz at room temperature and increases to more than 23 dB at 25 K.

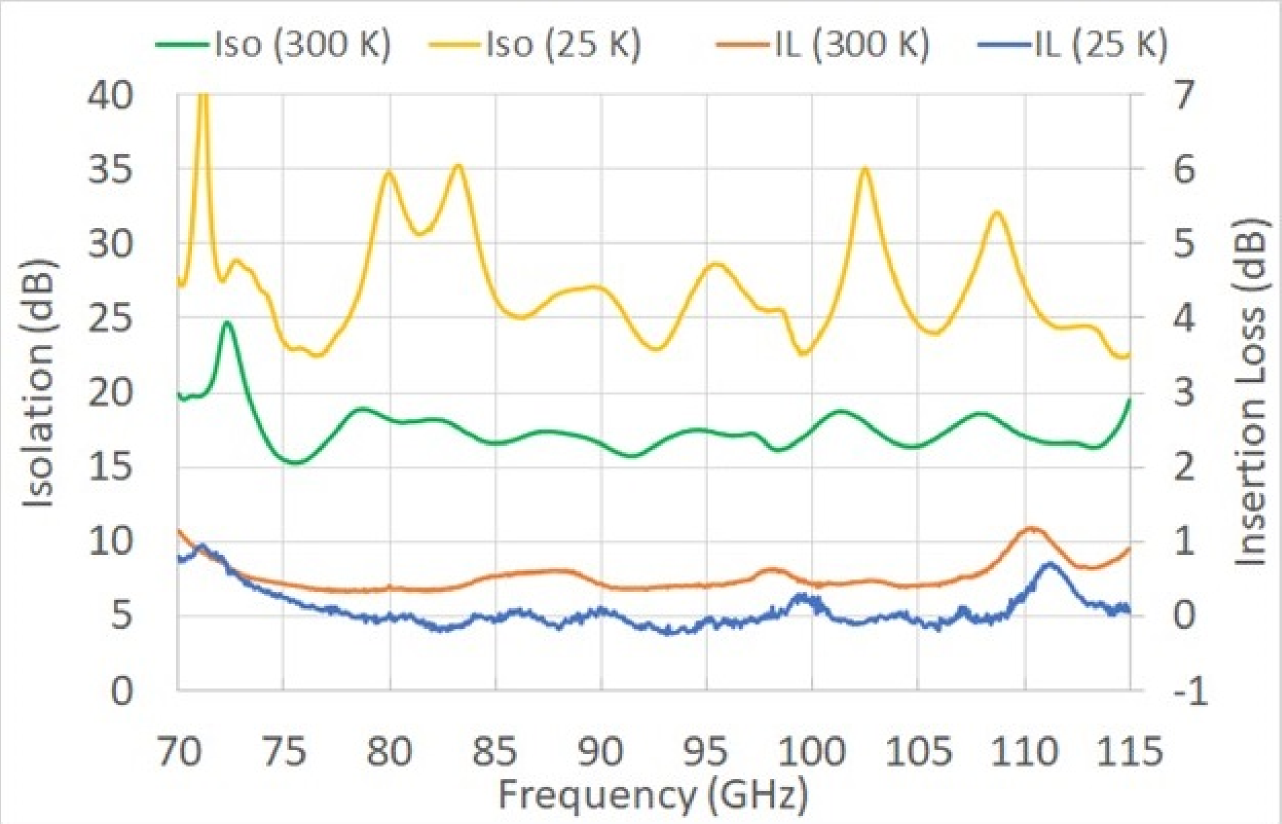


Figure 8. *Measured isolation and insertion loss for a Micro Harmonics WR-10 cryogenic isolator*

minima change with temperature, but the overall maximum reflection remains nearly constant at less than -17 dB across the entire tested band from 70-116 GHz. This equates to a VSWR of less than 1.3:1.

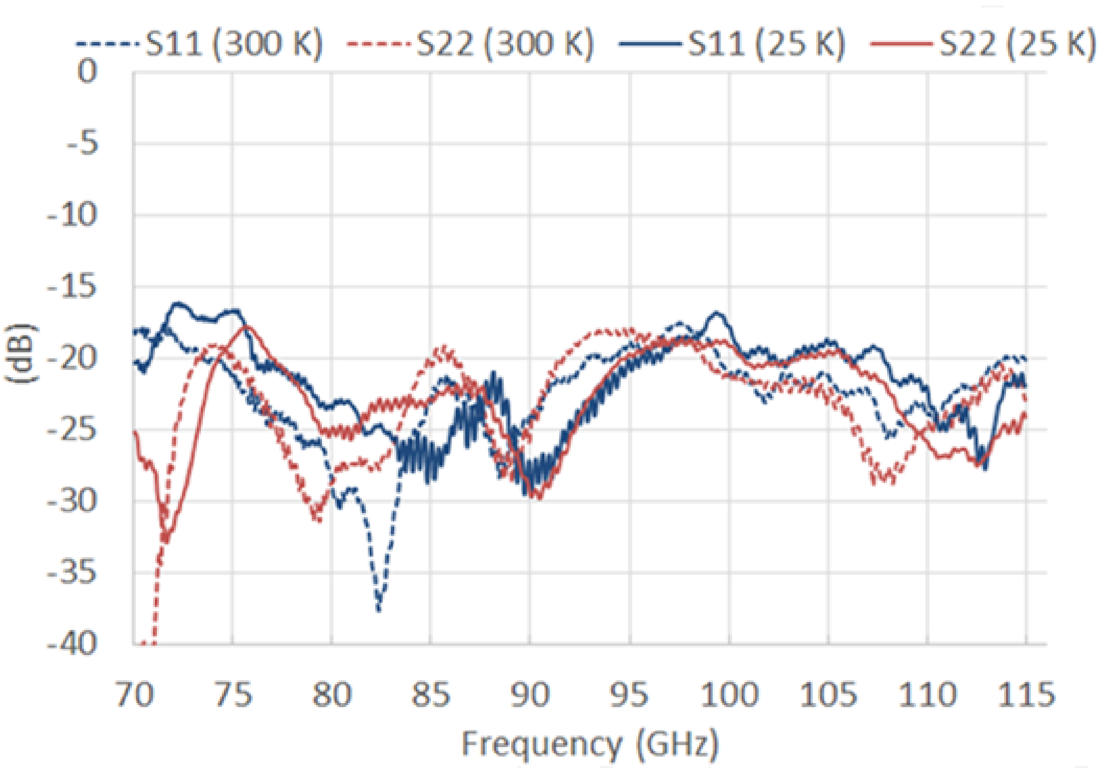


Figure 9. *Measured output port reflection for a Micro Harmonics WR-10 cryogenic isolator*

Summary

There are many important considerations that go into the design of a cryogenic Faraday rotation isolator. The temperature dependence of the ferrite material, thermal stresses, and minimizing insertion loss are all primary considerations. Micro Harmonics Corporation now offers a full line of cryogenic isolators from the WR-28 band (26-40 GHz) all the way to the WR-5.1 band (140-220 GHz). These cryogenic isolators offer the lowest insertion loss on the global market by a wide margin. The performance is routinely analyzed down to 25 K in our laboratory and has been verified by several other research institutions down to 1 K. Measured test data taken at 25K and 295K (room temperature) is supplied with every cryogenic isolator.

The Micro Harmonics cryogenic isolators are also the most compact available on the commercial market which means they don't take up much space on the cold plate. They have been carefully designed to withstand the rigors of cryogenic cycling which has been experimentally verified through hundreds of successful cryogenic cycles without a single recorded failure. Although specifically designed for use at cryogenic temperatures, they also give reasonably good performance at room temperature. These isolators are currently being used in radioastronomy telescopes and other high-profile research instruments around the world.

Acknowledgments

We would like to thank NASA for their support of this work through research contracts NNX15CP37P, NNX16CP07C, and 80NSSC18P2018, and the Virginia Innovation Partnership Corporation (VIPC) for their support through CRCF research grant SBIR20-013-US.

References

[1] Ferrite TT2-111, Trans-Tech Corporation, Adamstown, Md.

[2] High Frequency Structure Simulator (HFSS), 3D EM simulation, Ansys Corporation.

[3] R.N. Bhowmik, K.S. Aneeshkumar, "Low temperature ferromagnetic properties, magnetic field induced spin order and random spin freezing effect in Ni1.5Fe1.5O4 ferrite," Department of Physics, Pondicherry University, India.

[4] K. Maaz, A. Mumtaz, S.K. Hasanain, M.F. Bertino, "Temperature dependent coercivity and magnetization of nickel ferrite nanoparticles," Jrnl. of Mag. and Mag. Mat., 322, 2010, pp. 2199–2202.

[5] K.J. Strnat, D. Li, and H. Mildrum, "High and Low Temperature Properties of Sintered Nd-Fe-B Magnets," Paper no. VIII-8 at the 8th International Workshop on Rare Earth Magnets and Their Applications, Dayton, OH, 6-8 May, 1985.

[6] N. R. Erickson, "Very low loss wideband isolators for mm-wavelengths," in IEEE MTT-S Int. Microw. Symp. Dig., Phoenix, Az., vol. 2, 2001, pp. 1175-1178.

Click here to view cryogenic isolators from Micro Harmonics.

Click here to learn more about the use of cryogenic RF components.

Tags Isolator Cryogenic