Very Low Loss Wideband Isolators for mm-Wavelengths

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Abstract — **Isolators based on Faraday rotation in a cylindrical dielectric waveguide have long been used for full waveguide band coverage, but the typical loss has been significantly higher than for Y junction designs. A modification of the Faraday rotation design using better mode conversion and a greatly reduced ferrite length has resulted in much lower loss and better VSWR while maintaining high isolation. The performance is now comparable to the best narrow band Y junction designs but with nearly full waveguide bandwidth, and with even smaller size. The best WR10 units have a loss of 0.5-0.8 dB across the 75-110 GHz band, and a WR5 design has 1.0-1.2 dB loss from 160-180 GHz, increasing to 2 dB at 220 GHz. A further modification to the design using a diamond heat sink to dissipate high power has also been developed. These isolators work at cryogenic temperatures with somewhat lower loss.**

I. Introduction

Isolators based on Faraday rotation in a dielectric waveguide were demonstrated by Barnes [1] in 1961. Since that time this design, with few changes, has become an industry standard for full waveguide band isolators [2]. The advantage of Faraday rotation is that it has no inherent frequency dependence as long as the frequency is far above the Larmor resonance, and the propagating mode is TEM. If the wave propagates in a cylindrical dielectric (ferrite) waveguide, the mode is well confined within the ferrite over a wide frequency range, and the mode is nearly TEM in its behavior. The primary difficulty in obtaining the expected performance is in efficiently coupling the mode into the dielectric rod, and in minimizing the ferrite loss.

The typical design uses a rather long ferrite rod of a diameter just large enough to allow confinement of the wave at the lowest frequency in the band. The rod is magnetized with an axial field well below the saturation value. The ferrite used is a nickel ferrite [3] with a low loss tangent in the mm-wave range and a saturation field of about 5000 gauss. Coupling into the rod is done with tapered dielectric rods (typically alumina) which match the dielectric constant of the ferrite and which extend into the open ends of standard rectangular waveguides. The input and output waveguides are rotated by 45° relative to each other so that a reverse traveling wave will be polarized perpendicular to the waveguide at the output. Any reverse wave is absorbed by a metal film embedded in the dielectric tapers. This film is aligned so that it is perpendicular to the electric field for the forward wave, and parallel for the reverse.

II. Effect of Shorter Ferrite Rod

The improved design evolved out of the conventional design and many elements are in common. All of the general design details provided here apply specifically to a WR10 design, but most aspects scale readily with frequency. The ferrite rod diameter was maintained the same ($\varphi = 0.29\ \lambda$ at the lowest frequency) and the alumina tapers (11° full angle) were unchanged except to remove a cylindrical extension. The first change was to shorten the ferrite length as previously reported in a receiver application [4]. The equation relating rotation to field and length is:

$$\theta = \frac{4\pi M_z \gamma l \sqrt{\varepsilon}}{2c}$$

where $4\pi M_z$ is the axial magnetization, γ is the gyromagnetic ratio = $8.795\times10^6\times g$ rad/sec oer, (where g is 2.11 for TT2-111), l is the ferrite length, c is the speed of light, and ε is the dielectric constant of the ferrite. For the material TT2-111, the manufacturer gives $\varepsilon = 12.5$ at 9.4 GHz, while Kocharyan et al [5] give a 70-100 GHz averaged value of 14.1.

From this equation (and the data of [5]) the minimum length for 45° rotation at saturation ($4\pi M_z = 5000$ gauss) is 1.35 mm, although this conflicts slightly with data later in this paper. The conventional design uses a 6.3 mm length, so it is possible to shorten the ferrite substantially. This large reduction in ferrite length reduces the loss by a factor of 2 or more, and shortens the isolator by nearly 5 mm. A cross section through this device is shown in Figure 1.

As the ferrite rod changes from a long needle shape to a length-to-diameter ratio near 1.5, the internal field becomes much less homogeneous. The field rotation across the wave becomes non-uniform, and should create higher modes, except that the ferrite is not large enough to propagate any axially symmetric higher modes. Thus field uniformity is not very important, as long as the field is axially symmetric. There is some experimental evidence that a less uniform field leads to slightly higher loss.

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The magnetic design is quite simple. Two to four NdFeB or SmCo magnets around the perimeter of the ferrite rod assembly are coupled together with iron disks having a small hole on their axis. This produces a fairly uniform field which is nearly purely axial at the location of the ferrite rod. The hole in the disks is just large enough to admit the (nonmagnetic) metal waveguides coupling to the ferrite. Two magnets with a length of 3 mm and diameter of 4.5 mm produce a nearly saturating field in the ferrite, while the field is well saturated with four magnets.

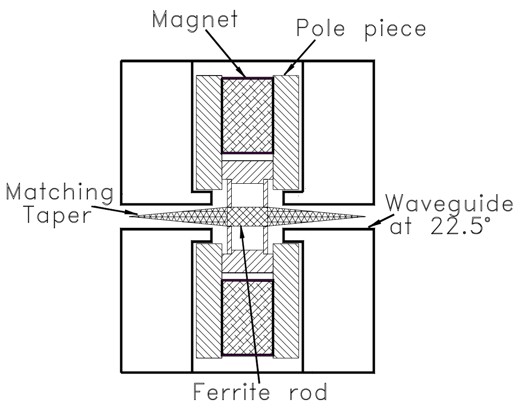

Fig. 1. Isolator design showing the short ferrite version, before the addition of mode suppressors and stepped twists.

III. Mode suppressor

The second significant electromagnetic innovation is a way to better control the mode transition from the metal waveguide to the dielectric tapers. Since the transition to the tapers was already fairly efficient, this was approached as just a modification of the geometry. A study using HFSS [6] showed that the dominant source of loss in this transition was to the sixth order mode, which had no significant axial symmetry. Adding a cylindrical section of metal waveguide to the transition region surrounding the dielectric taper worked well to suppress this mode. Dimensions of the cylindrical section were changed in HFSS until the transition showed the least mode conversion to any higher mode over the widest bandwidth. These studies were initially done with a nearly ideal geometry in which the dielectric taper ended at the joint with the ferrite, and there was no mechanical support for the rod. The metal cylinder has a diameter of 1.88 mm and a length of 1.07 mm, and ends 0.3 mm from the end of the taper. Predictions showed that the mode conversion could be less than 1% of the incident power from 80-115 GHz.

Adding a support for the ferrite rod can significantly degrade the transition because the best mechanical location is exactly at the ferrite to taper joint. The best material for the support in terms of strength and relatively low loss is polystyrene, fiberglass or a similar plastic, and with a thickness of 0.25 mm, this leads to a considerable amount of mode conversion. The solution was to make the support thinner, and at a thickness of 0.08 mm the problems are greatly reduced. Such a thin support is practical using mylar [7], which is quite strong in thin films. The assembly of the isolators is sensitive to the exact location of this mylar support and the amount of glue used to attach the ferrite-taper assembly to the support.

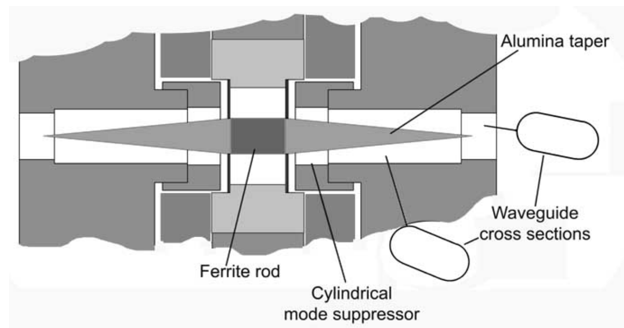

Fig. 2. Cross section detail through the isolator with mode suppressor and stepped twist.

IV. Stepped waveguide twists

The intermediate design [4] eliminated the waveguide twists required to realign the waveguides (after the 45° internal rotation). Instead, the end waveguides were simply straight sections each aligned with a 22.5° angle relative to the flange. This produced a small mismatch at the flange, which added to the internal mismatch to produce an overall return loss of as little as 16 dB from 85-115 GHz. An improved transition is now used with a stepped twist to reduce the effect of the 22.5° rotation. A waveguide is milled into the block by simply plunging into the block with a cutter, leaving radiused waveguide corners. This waveguide continues over the length of the dielectric taper. From the other side of the waveguide block a second waveguide is milled in the same way at a 11.2° relative angle for a length of a quarter wavelength. This waveguide block is easier to manufacture than the previous design, and the performance is much better. The return loss of the improved isolator is >19 dB from 85-115 GHz, with consistently better performance in the midband.

V. Performance

The performance of a complete WR10 isolator of the new design is shown in Figure 2. The overall length of the isolator is 15 mm with a cross section the same as a WR10 flange (20x20 mm). The ferrite rod length is 1.78 mm (somewhat greater than the minimum) to make adjustment of the rotation possible with the applied field. The match degrades below 85 GHz largely because the application did not require this part of the band, but instead required good performance up to 115 GHz. The quality of the match is determined in part by the tuning of the stepped twist. Below 73 GHz the behavior deteriorates rapidly because of the undersized dielectric waveguide. About 40 of these isolators have been built and this performance is typical of about half of the production. The poorer units have about 50% higher insertion loss. One feature of this design is the very high isolation. All of the units show >25 dB isolation, with 30 dB being typical.

The pole pieces used to confine the field result in a fairly well-shielded magnetic field, permitting these isolators to be close packed with minimal interactions. Placing two isolators against each other has a negligible effect on loss and only decreases the isolation from 30 dB to 25 dB.

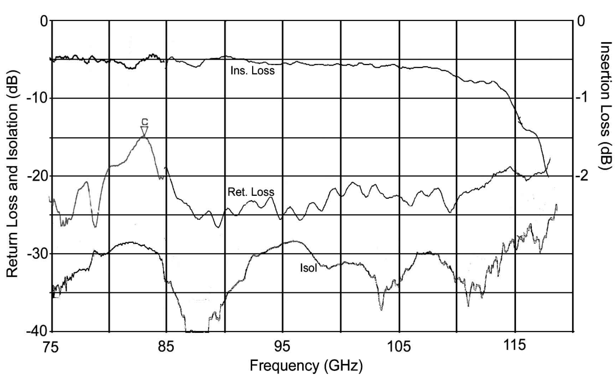

Fig. 3. Room temperature behavior of a WR10 isolator, designed for the range 85-115 GHz. Note the separate scale for insertion loss.

An approximate copy of this design was built in the WR5 band by scaling of most of the electromagnetic design, but with a considerable amount of mechanical redesign. The isolator has the same 20x20 mm cross section but a total length of only 9.5 mm. The ferrite length is 1.52 mm, requiring a nearly saturating field. The loss is much lower than any previous design. Two of these units have been built with similar behavior. The measured loss of one is shown in Figure 3. The design does not optimally cover all of WR5 because this is a wider fractional band than WR10. The loss shows a significant increase at the higher frequencies probably because of the increasing ferrite loss. The resonances near the low end of the band are due to mode conversion, in part made worse by the relatively thicker mylar supports (0.05 mm) and the glue used to attach the rod. The more difficult assembly may lead to additional loss because of misalignment. The isolation is >25 dB but is difficult to measure to a greater level in this band.

Potentially this design may be scaled even higher in frequency. The loss scales to ~2 dB at 300 GHz, using the trend from lower frequency data. The mechanical tolerances are tight but feasible in WR3.

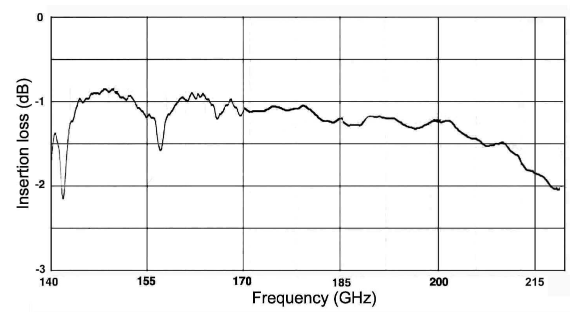

Fig. 4. Room temperature insertion loss of a WR5 isolator.

VI. Material properties

This work may be used to confirm some properties of the ferrite material. The return loss of this isolator design is dependent upon achieving a good match between the dielectric constant of the ferrite rod and that of the matching taper. The quality of the return loss indicates that the dielectric constant of this material is not as high as 14.1, and in fact it can not be above 12.2 assuming that the dielectric constant of alumina is 9.9. Otherwise this reflection alone would produce a return loss >-20 dB.

The predicted minimum length of 1.35 mm (using $\varepsilon = 14.1$) also is shorter than experimentally observed. Based on the measurement of rotation vs length in the 150-210 GHz band, it is believed that the minimum ferrite length is 1.45 mm, and this is consistent with $\varepsilon = 12.2$, assuming all other values are correct. It should be noted that this ferrite material is somewhat variable, and all properties are likely to vary from batch to batch.

VII. High power applications

A problem with this design is that the very thin disks used to support the rod have very little thermal conductivity. Much all of the thermal path to ground is through the conduction of air. This has always been the case with this type of isolator, but the older design had a much longer ferrite rod and thicker support disks. Power amplifier MMIC's are now available producing up 0.4 W at 100 GHz, and these may be used with this isolator in one space application. In vacuum, the thermal conduction will be dominated by radiation and the temperature rise may be very large in the event of a large reflection. In fact these isolators have been successfully used with an input power of 200 mW in vacuum, but the dissipated power is unknown.

To eliminate this problem an improved support disk has been designed using a thin diamond film. HFSS simulations show that a diamond disk (ε = 5.7) of thickness 50 μm may be substituted for the mylar disk, with the diamond sandwiched between the dielectric cone and the ferrite rod, and the performance is only modestly degraded. Sandwiching the diamond between parts greatly increases the heat transfer through the epoxy, and has little effect on performance, relative to a ring outside the ferrite. Thin diamond films are readily available using CVD growth [8]. Only one diamond disk is needed since only the input taper dissipates any significant power, and a single disk is sufficiently strong to support the assembly. In an ideal isolator the resistive film in the taper on the output end never dissipates any power because it is aligned perpendicular to the electric field. The taper on the input end terminates all of the reverse power. The ferrite rod dissipates at most 10%.

A test of this concept was performed using a 90 μm thick film (the thinnest standard part), and the resulting isolator worked much as predicted. The insertion loss varies from 0.7-1.0 dB from 80-109 GHz. The output return loss is much like the data in Figure 3, but the input RL degrades to 17 dB at 109 GHz. This device is useful as it is, but better results are expected with thinner films. The thermal conductivity of CVD diamond is not so great as for the bulk material but is still better than copper. Thus the temperature rise in this device is limited by the properties of glue joints rather than the disk itself. A detailed thermal analysis [9] shows that this design can safely dissipate 0.4 W in vacuum at room temperature.

VIII. Cryogenic applications

These isolators may be cooled to 20K or less, and few of the properties change. The loss of the ferrite decreases somewhat, as do other circuit losses, and the total loss decreases to ~80% of that at room temperature. The primary change is in the saturation field of the ferrite which appears to increase ~20% (based on the measured rotation of a strongly saturated ferrite), although the manufacturer's data [3] indicates a much larger change. The bias field from the magnets also increases about 10%. These changes mean that any isolator built for room temperature will be somewhat mistuned when cold, with the greatest change for the shortest ferrite lengths. In practice it is found that for a ferrite of 1.7 mm length, the field may be set to give >25 dB isolation warm or cold, by biasing at slightly below optimum field at room temperature. For cryogenic applications the shortest possible ferrite length is 1.25 mm, but the isolation will be quite poor at room temperature.

IX. Conclusions

These results show that very low loss wideband isolators are practical throughout the mm-wave bands, and that these devices offer superior performance in all other respects as well. An insertion loss as low as 0.5 dB is measured near 90 GHz, and 1.0 dB near 160 GHz. Isolation is typically 30 dB, and return loss 20 dB. These devices work well at cryogenic temperatures, with even lower loss. Using diamond heat sinking, very high power may be handled with reduced bandwidth. Most of this work has been aimed at specific applications, rather than standard waveguide bands, but serves to show what is possible. Potentially even higher frequencies are practical with a scaling of the design although this will require very tight mechanical tolerances.

Acknowledgement

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