MINIATURE CIRCULATORS FOR MICROWAVE SUPERCONDUCTING SYSTEMS

A. Fathy, E. Denlinger, D. Kalokitis,V. Pendrick, H. Johnson *
Alberto Pique', K. S. Harshavardhan, E. Belohoubek++

* David Sarnoff Research Center, Princeton, N.J.,08543
++ Neocera, INC., College Park, MD, 20742

ABSTRACT

Ultraminiature high performance lumped element high temperature (HTS) circulators have been successfully demonstrated. Epitaxial HTS YBCO films have been deposited by pulsed laser deposition (PLD) onto buffered Yitrium Iron Garnet (YIG) substrates with measured surface resistance values (<1mΩ at 10 GHz @ 77K) comparable to those of HTS films on lanthanum aluminate. The lumped element circulators occupy an area about an order of magnitude smaller in size than that of conventional disc junction circulators. Excellent low loss (< 0.23 dB) and high isolation (>30dB) over 5% bandwidth have also been demonstrated.

ACHIEVEMENTS

We have successfully demonstrated high performance, ultraminiature lumped element HTS circulators at Ku-band. Epitaxial, highly oriented YBCO HTS thin films were deposited together with their buffer layers onto low loss single crystalline (001) oriented YIG substrates. The area of the lumped element circulator's circuit was about one-tenth that of a conventional microstrip disc junction circulator.

Circulators are extremely important components in the chain of complex microwave systems. Little previous effort has been directed toward superconducting circulators. Meanwhile, a long list of various passive and active superconducting components have enjoyed a tremendous amount of development and success. Filters [1], multiplexers [2], and low noise receivers [3] are examples. Superconducting circulators can be vital in integrating various superconducting components serving to reduce interaction problems on integrated systems assemblies.

Preparation of high quality HTS thin films on low loss garnet substrates makes possible the direct integration of high performance passive microwave components with non-reciprocal devices, all on the same substrate [4]. Garnet ferrites are preferred in this application for: their lower losses, smaller anisotropy, no magnetic disorders in the crystal structure, temperature stability and broad bandwidth operation.

We have chosen single crystal YIG since it exhibits high saturation magnetization ($4\pi M_s \sim 1780$ gauss), high remanent field ($4\pi M_r \sim 1277$ gauss), good hysteresis squareness ratio of 0.72, low microwave dielectric loss tangent ($\tan\delta < 0.0005$), narrow magnetic line width of about 20 Oersteds (which ensures low microwave magnetic loss), low coercive force of 0.45 Oersteds (which minimizes the energy needed for switching the field in the ferrite), and a thermal expansion coefficient ($\alpha = 11\text{x}10^{-6}/^{\circ}C$) which is close to that of YBCO ($\alpha = 11\text{x}10^{-6}/^{\circ}C$) [5].

The YIG substrates used here were purchased from Deltronic Crystal Industries. The substrates were 1cm x 1cm x 0.025 cm in size and cut with the (001) direction normal to the plane (this direction is critical in order to achieve good epitaxy between the YBCO film and the substrate [5]). Due to the fact that YIG is a relatively soft material and cleaves easily, handling of these very thin substrates through the deposition, evaluation, patterning and final device assembly was very difficult. However, YIG substrates with thickness of 0.025 cm were required to operate at Ku-band frequency range without moding.

HTSC circuits were fabricated using conventional photoresist techniques. The circulator pattern is formed by coating the YBCO with photoresist, exposing and developing the pattern. The unwanted superconductor is removed by ion milling in Ar^+. Gold contacts are then formed using a modified lift-off process. Finally a normal metal ground plane is deposited on the back of the substrate.

Excellent surface resistance values (similar to YBCO on lanthanum aluminate substrates) of 0.5 to 1 mΩ at 10 GHz have been measured by the dielectric resonator technique at 77K (see Fig. 1). Relatively high critical current densities for these films were measured in the presence of transverse magnetic fields at 77K. The measured critical current density was $1.1\text{x}10^6$ A/cm^2 at 0.2 Tesla as compared to $2.7\text{x}10^6$ A/cm^2 at zero applied field (see Fig. 2) [5]. These high quality films maintain their low surface resistance while

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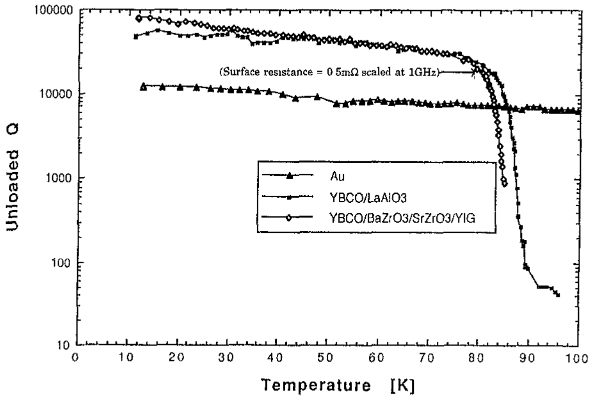

Figure 1. Unloaded Q vs. temperature for 1cmx 1cm films deposited onto buffered YIG substrates measured by the dielectric resonator technique at 25 GHz. Measurements corresponding to gold on LaAlO3 and a high quality film on LaAlO3 are included for comparison.

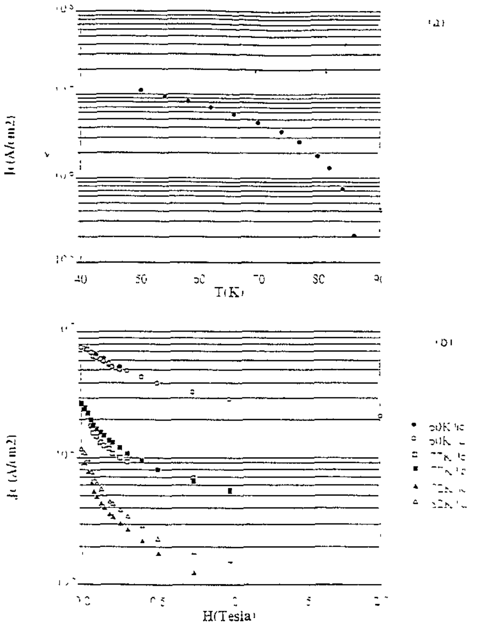

Figure 2. (a) J_c as a function of temperature for a $YBCO/BaZrO_3/SrZrO_3$ YIG structure. (b) J_c vs. external magnetic field for the same sample, IIc indicates that the field was applied parallel to the x-axis of the YBCO film and IIa indicates that the field was parallel to the YBCO a-b plane.

subject to the required dc bias magnetic fields.

We have measured the relevant characteristics of YIG substrate samples that are pertinent to microwave performance at 77K. We used a dielectrometer to measure the dielectric constant and the loss tangent of the single crystal YIG, and their values at 77K were 16 and $5x10^{-4}$, respectively. A sample of YIG was also measured by NRL using a vibrating sample magnetometer technique. These measurements indicated an increase in the value of $4\pi M_s$ to 2370 Gauss at 77K as compared to 1780 Gauss at room temperature which must be taken into account at the design stage.

We pursued two circulator designs: a conventional disc circulator and a lumped element circulator utilizing polycrystalline YIG, both with normal copper metalization. The design of the cryogenic conventional disc junction circulator is based on Fay and Comstock's design equations [6], where the $4\pi M_s$ of the YIG material at 77K was used. Single section quarterwave matching transformers were used (see Fig. 3) to obtain bandwidths of approximately 5% at 12.5 GHz. At 77K the circulator's measurements indicated a 0.3 dB insertion loss, and over 45 dB return loss at midband (see Fig. 4). Circulator performance was in excellent agreement with theoretical predictions. For the quasi-lumped element circulator, we used a 12 GHz design that was scaled from a lumped element circulator design at 1.6 GHz [7] (see Fig. 5). The circulator showed an insertion loss of 0.56 dB and 37 dB isolation at midband as shown in Fig. 6). The relatively high insertion loss is related to the extremely narrow lines in the inductive section and the magnetic loss of the polycrystalline YIG substrate. Superconducting lumped element circulators on single crystal YIG substrates can overcome these problems.

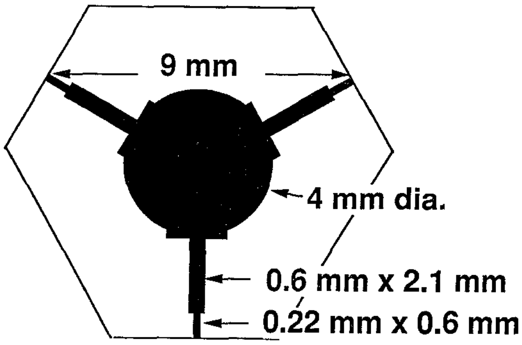

Figure 3. Circuit layout of conventional disk circulator.

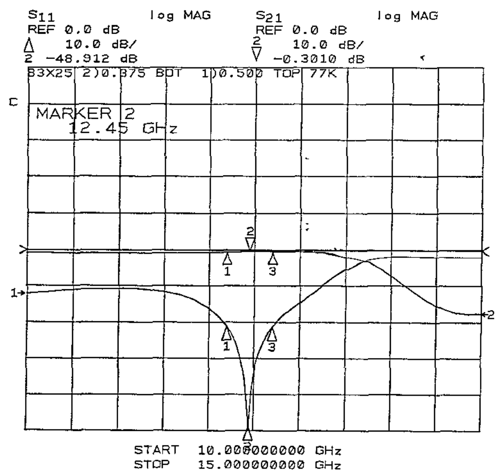

Figure 4. Insertion loss and isloation of conventional YIG circulator.

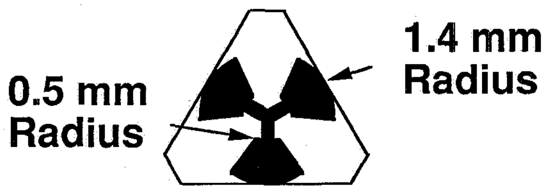

Figure 5. Quasi-lumped element circulator. Notice the difference in size between circuits (shown to scale).

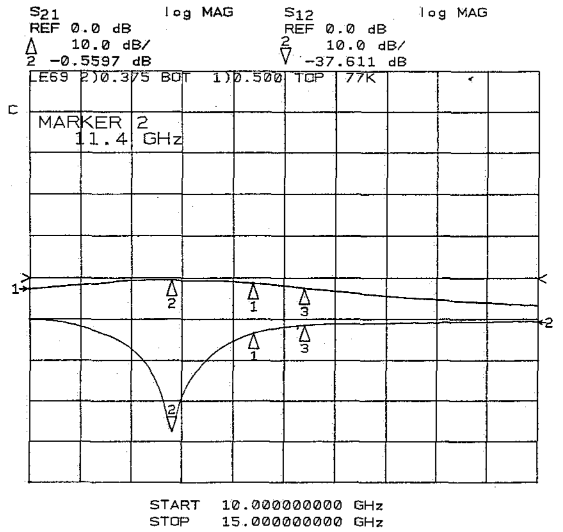

Figure 6(a). Insertion loss and isolation of quasi-lumped element circulator with copper metallization at 77K.

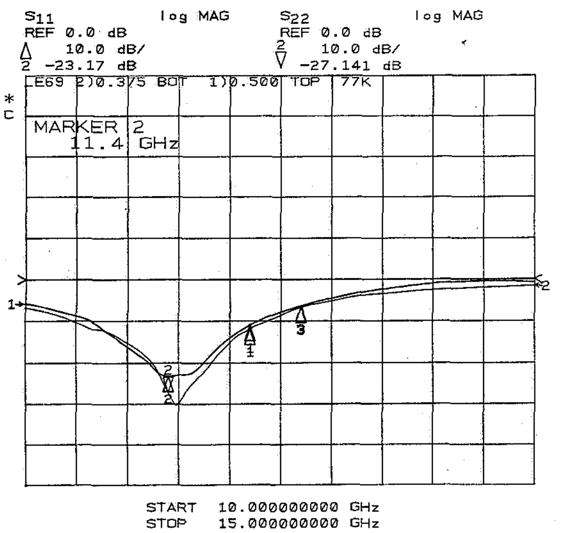

Figure 6(b). Return loss of quasi-lumped element circulator with copper metallization at 77K.

The superconducting lumped element circulator occupies an area almost an order of magnitude smaller than that of the conventional circulators (see Fig. 7). The use of superconducting lines eliminates the relatively high loss that occur in the narrow lines of the lumped element design. Meanwhile, the use of single crystal YIG reduces the magnetic loss as its magnetic linewidth ΔH is significantly reduced at 77K [8]. As predicted, excellent performance was achieved using single side HTS films deposited onto YIG substrates, where the insertion loss was reduced to 0.23 dB, and the 20 dB isolation bandwidth is still at 5% (see Fig. 7). Use of YIG substrates with HTS films deposited on both sides will further improve the circulator insertion loss performance.

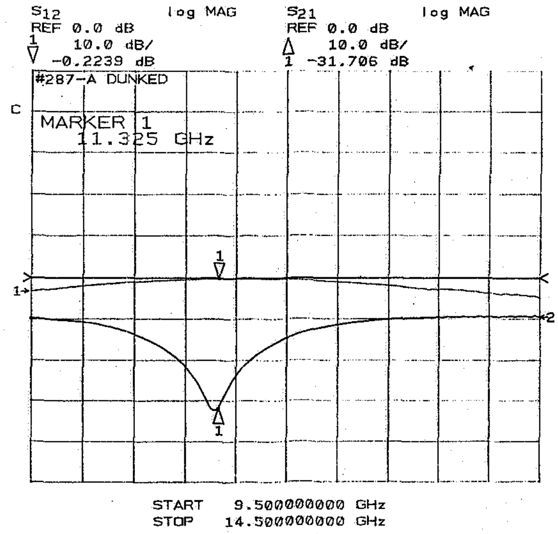

Figure 7(a). Insertion Loss S_{12} and Isolation S_{21} of HTS Circulator 287-A.

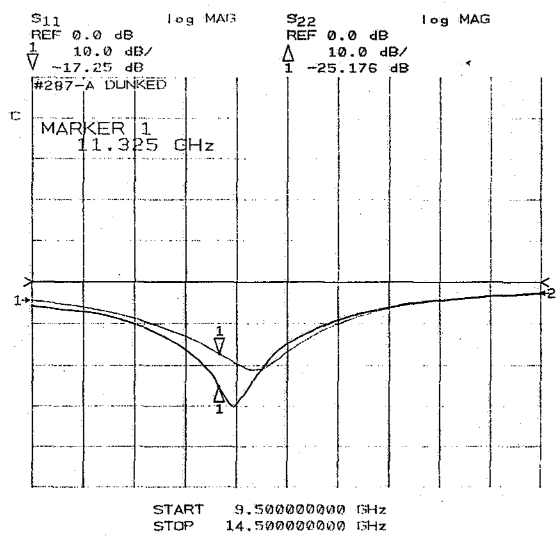

Figure 7(b). Input Return Loss S_{11} and Output Return Loss S_{22} of HTS Circulator 287-A.

CONCLUSIONS

Excellent YBCO films on YIG substrates have been developed for the fabrication of HTS circulators. Both conventional and lumped element circulators can significantly benefit from the lower conductor loss attainable using HTS technology. Lumped element circulator implementation is an important step towards both miniaturization and integration of complex microwave systems. Pushing this technology towards the use of large area high quality YIG substrates is crucial at this stage, and in the future, use of double side deposited HTS films will further improve the performance of these circulators.

ACKNOWLEDGMENT

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