Superconducting Nonreciprocal Devices for Microwave Systems

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Abstract—**The feasibility of applying high-temperature superconductor (HTS) technology to nonreciprocal microwave devices has been demonstrated for the first time. Such devices in the form of isolators and circulators are used widely to achieve stability, reliability, and reproducibility in microwave circuit performance. The experimental X-band device, a three-port stripline circulator consisting of a thin sapphire substrate coated with a YBCO film and sandwiched between two ferrite disks, showed low insertion loss (0.25 dB) and very high isolation (>30 dB) at an operating temperature of 77 K. This technology permits the integration of many HTS microwave components together with nonreciprocal devices on a common substrate.**

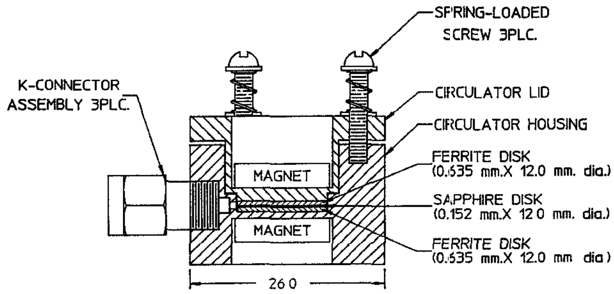

Fig. 1. Assembly view of HTS circulator.

I. Introduction

The DISCOVERY of the new high-temperature superconductor (HTS) materials promises to lead to major improvements in passive microwave circuits with respect to making components smaller and lighter with reduced losses. However, truly enabling benefits will not likely be derived from simple replacements of existing components with HTS counterparts, but rather from a comprehensive systems approach which integrates a number of HTS components into a cooled subsystem. In this letter, we demonstrated the feasibility of applying low-loss HTS technology to microwave nonreciprocal devices.

The objective of this effort was to demonstrate a small volume HTS circulator that takes advantage of high-quality HTS films on buffered sapphire substrates. Circulator action is achieved by sandwiching a very thin sapphire substrate between ferrite disks in a stripline configuration.

II. Circulator Design

The conventional stripline circulator design consists of a circular center conductor, ferrite discs on both sides, and quarter-wave matching transformers at each port. The circular junction is a ferrite-loaded resonator and can be represented by a cylindrical cavity with "electric walls" at the ends and a "magnetic wall" on the circumference. If the ferrite discs were considered pure dielectric (or demagnetized ferrite with isotropic permeability and dielectric constant), the solution would produce pairs of counter-rotating modes which are degenerate in the cavity. However, upon introduction of a magnetized ferrite with a tensor permeabiliy, the resonant frequencies $f(+)$ and $f(-)$ of the two counter-rotating modes are split. The bandwidth of the circulator is proportional to the magnitude of the splitting caused by the ferrite. If only a fraction of the cylindrical cavity is ferrite and the rest filled with a pure dielectric of about the same dielectric constant, then there will be less frequency splitting of the modes and less bandwidth.

An implementation of a partially ferrite-filled circulator resonator is shown in Fig. 1 where a sapphire substrate with the HTS conducting pattern is continued right through the circular junction. The HTS substrate is made as thin as practically possible ($\approx$ 100 μm) in order to maximize the ferrite filling factor and the bandwidth. This technique avoids the necessity of depositing the HTS conductors directly on the ferrite discs, which has not been successfully done thus far.

The material chosen for this circulator is TT2-125, a nickel ferrite manufactured by Trans-Tech, Inc. This material has a saturation magnetization ($4\pi M_s$) of 2100 Gauss and a dielectric constant (ϵ_r) of 12.6. For operation at 10 GHz, equations from [1.3] were used to design the circulator with a disc junction diameter of 6.1 mm and a disc thickness of 0.635 mm. With optimized quarter-wavelength transformer lines at all circulator ports, the total ferrite diameter was 12 mm. Two 12.5-mm diameter, 3.1-mm thick samarium cobalt magnets, one above and one below the ferrite disks, were used to saturate the ferrite with a dc magnetic field.

III. Circulator Fabrication

The requirement for a high-quality HTS film on a very thin substrate led to the selection of sapphire as the substrate material. Sapphire is widely available, has very low loss, and

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because of its high strength can be polished into very thin wafers. For depositing YBCO on sapphire, CeO_2 was chosen as a buffer [4]. The 0.152-mm thick sapphire substrates were coated by pulsed laser deposition, first with a CeO_2 buffer layer about 100-nm thick and then with a YBCO layer about 250-nm thick under a single pump-down cycle. The thin sapphire substrates survived the deposition process without any signs of cracking. The CeO_2 layer was deposited at around 900° C as measured on the heater in an O_2 partial pressure of 300 mTorr. The temperature was then lowered to 800°C and the O_2 pressure adjusted to 250 mTorr in order to deposit the YBCO layer. Once the YBCO layer was completed the O_2 pressure was increased to 300 mTorr and the heater ramped down to room temperature. Each of three films showed similar transition curves as measured by ac susceptometry. Transition onsets were at about 89.5 K and the width of the transitions were about 0.5 K.

A cross-sectional view of the circulator is shown in Fig. 1. Standard techniques were used to pattern the YBCO circuit on the sapphire using photoresist. Ion beam milling was used to remove the unwanted YBCO and buffer layer. The housing and lid of the circulator are machined from 6061 Aluminum stock and then gold-plated. A small length of gold ribbon is welded to the K-connector glass beads and then these beads are soldered into the housing. The lower ferrite disk is inserted into the housing, then the sapphire disk with the superconductor pattern facing upwards is inserted, and the gold ribbons are attached from the glass beads to the superconductor on the sapphire. The top ferrite disk radius is cut back 0.25 mm in in the area over the three connector lines to prevent the gold ribbons from being crushed. A thin piece of indium foil is placed over the upper ferrite disk to provide a uniform ground plane when the lid is in place. The lid is secured with three spring-loaded screws for mechanical stability of the lid pressure over temperature. The two samarium cobalt magnets are inserted as shown in Fig. 1.

This design proved to be mechanically stable, provided reproducible microwave measurement results and could be repeatedly cycled to low temperatures without any breakage.

IV. Experimental Results

Initially, a sapphire substrate with copper metallization was fabricated to test the circulator design and verify the losses of the copper version. The insertion loss of this device is 0.46 dB and the peak isolation is 25.3 dB (both at 77 K). Two samples using $YBaCuO_3$ films on sapphire were subsequently prepared and measured. At 77 K, the insertion loss of an HTS sample was 0.49 dB and the peak isolation 34.1 dB. The insertion loss is equivalent to that of the copper unit within the measurement tolerance of the test system. All measured data shown in Fig. 2 included the loss of the connectors which was measured to be 0.25 dB per pair at 300 K. The insertion loss of the circulator was also measured as a function of temperature and showed a steep transition starting at 89 K. The high-transition temperature and sharpness of the transition is a clear indication that excellent superconducting performance can be obtained in the presence of high-transverse magnetic dc

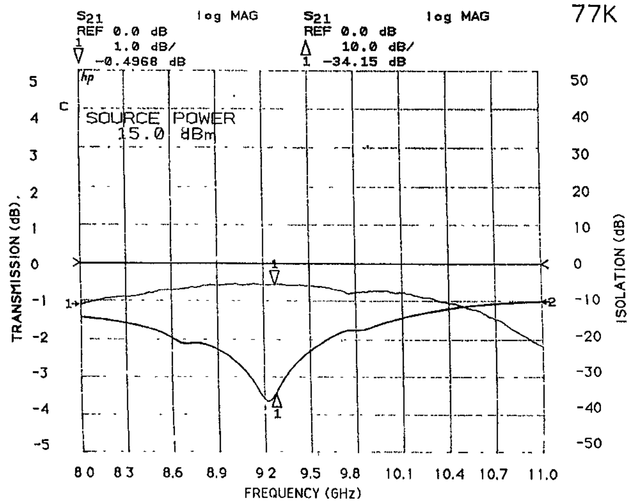

Fig. 2. Insertion loss and isolation of the HTS circulator.

fields. This finding is also corroborated by measurements of the microwave surface impedance as a function of dc magnetic field performed by J. Steinbeck of Rome Laboratory [5].

The insertion loss in the present experimental circulator at 77 K and below is dominated by the magnetic loss of the ferrite substrate material and the fact that the ground planes are made of copper. The particular ferrite chosen for these early feasibility experiments was one readily available from previous circulator programs. The Trans-Tech TT2-125 ferrite with a linewidth (ΔH) of 460 Oe and a dielectric loss tangent of 0.001 is well suited for high-power applications but has fairly high-magnetic losses which, however, in normal circulators are not dominant. In superconducting circulators where extremely low insertion losses are important other materials may be a much better choice. A calcium vanadium garnet, for example, has a dielectric loss tangent of only 0.0002 and a resonant linewidth of 15 Oe. Theoretical calculations using [1] for the circulator junction and [6] for the matching transformer lines yield insertion losses of about 0.2 dB for the nickel ferrite and less than 0.1 dB for the calcium vanadium garnet.

V. Conclusion

We have experimentally deomonstrated the feasibility of using high-temperature superconducting (HTS) thin films in an X-band circulator operating at 77 K. This opens the possibility of integrating advanced HTS components together with very low-loss, nonreciprocal devices, all on the same substrate. The result promises to be a substantial weight and volume savings together with having better performance, reproducibility, and reliability.

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