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Measuring microwave shielding effectiveness in liquid nitrogen

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A technique to distinguish between materials that can and cannot shield microwaves in liquid nitrogen was developed. The samples are placed in a modified *X*-band waveguide, which operates by the same "insertion loss" principle as a coaxial device used to measure shielding effectiveness from 300 to 1000 MHz. Verification of the waveguide fixture was accomplished by measuring the shielding effectiveness of a good conductor, coppper; a nonconductor, Teflon; and two intermediate conductors, steel and a carbon-filled elastomer. After verification, the waveguide fixture was used at liquid nitrogen temperatures to compare the shielding effectiveness of $YBa_2Cu_3O_{7-x}$, a high temperature superconductor, with copper, a known shielding material.

I. INTRODUCTION

High temperature superconductors have attracted media attention in recent years due to their ability to conduct electricity with zero resistance at liquid nitrogen temperatures. This property makes them attractive as highly efficient electromagnetic shields; for example, in magnetic resonance imaging.[1] High temperature superconductors are expected to exceed existing materials in shielding effectiveness at low frequencies. Shielding effectiveness is a measure of the ability of a shield to exclude or confine electromagnetic waves. It is usually expressed as a ratio of the incident to the penetrating signal amplitudes in decibels. However, applied fields are radically altered when penetrating high performance shields and the measured amplitude depends on the type and position of the sensor. Therefore, measurement results are highly sensitive to the test procedure employed. When reporting "shielding effectiveness," a specific test and procedure should be referenced or details of testing procedure documented.[2] In addition, the sample parameters, such as thickness, should be included.

Each shielding test and procedure is applicable over a given frequency range. Three frequency ranges, 200 Hz—20 MHz, 300–1000 MHz, and 1.7–12.4 GHz, require very different testing procedures. Shielding effectiveness changes with frequency, and the numerical results from different procedures cannot be directly compared without accounting for differences in test specific factors, such as the angle of incidence, reflection at the interface, and sample thickness. The shielding capability of high temperature superconductors has been demonstrated at low frequencies (up to 10 kHz) using a device made with two coupled coils[3] and verified in our lab. A device to measure cryogenic shielding effectiveness in the mid-frequency range (300–1000 MHz) was developed at Belden Wire and Cable by modifying a flanged coaxial test fixture designed by the National Bureau of Standards, now the National Institute of Standards and Testing (NIST).[4] Thus far, shielding effectiveness of ceramic superconductors has not been adequately characterized in this frequency range, primarily due to the sample size requirements.[4] Flat samples, at least 9 cm in diameter, must be able to withstand considerable torquing when placed in the flanged device to utilize this technique.

The standard shielding effectiveness test for high-frequency shielding (1.7–18 GHz) is complicated and requires a shielding enclosure or cavity, a box made from the shielding material.[5] In addition, it is not well suited for cryogenic measurements. We have therefore developed a new procedure, using a waveguide fixture, to measure microwave shielding effectiveness. The procedure has many advantages over the standard high-frequency shielding effectiveness measurement procedure. It does not require a shielding cavity, which would be costly to construct repeatedly from high temperature superconductors. In addition, it can be used to determine shielding effectiveness at room temperature and in liquid nitrogen. It is the only technique available that can be used to determine if a material shields at liquid nitrogen temperatures and microwave frequencies. The technique is based on the same principle as the modified NIST coaxial design. However, the procedure measures shielding effectiveness at frequencies higher than the modified NIST fixture, and has three main advantages over the NIST procedure, due primarily to the smaller fixture dimensions. It requires less liquid nitrogen, less time to cool down, and it is easier to manipulate in liquid nitrogen. Most importantly, it requires smaller samples, only 3 cm by 2 cm. Flat, defect free ceramic samples can more easily be sintered to these specifications, making this technique more practical for quickly determining if a sample can shield in the microwave frequency range. The procedure can be used to verify the shielding capabilities of materials with interesting properties at cryogenic temperatures such as the high temperature superconductors or materials, which are be used in a cryogenic environment such as electronic equipment in space.

II. SUMMARY OF CLASSIC SHIELDING MEASUREMENT TECHNIQUES

Shielding effectiveness measurements below 10 kHz are made using two coupled coils. The coupling between the coils is measured with and without a sample between the two coils. A good shield significantly reduced the cou-

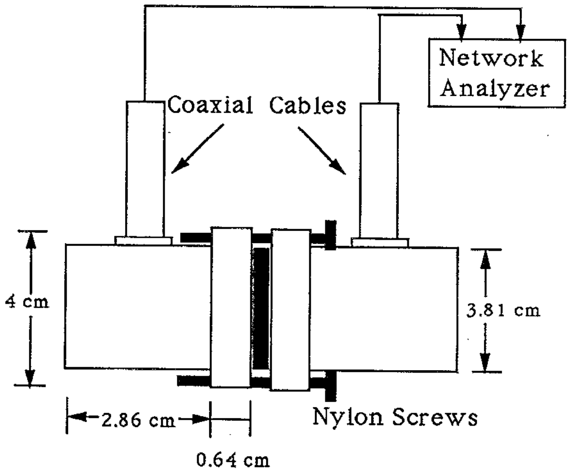

FIG. 1. Schematic of a waveguide fixture.

pling between the matched coils. This setup may be submerged in liquid nitrogen for cryogenic measurements.

The standard test for determining shielding effectiveness from 300 to 1000 MHz employs a flanged coaxial test fixture. The power transmission of the test fixture is measured with and without a sample in the fixture. The fixture was modified to allow liquid nitrogen to flow through the interior, and thus to the sample for cryogenic measurements. After calibration of the test fixture in liquid nitrogen, the procedure for cryogenic measurements is the same as that for room temperature measurements.

The standard test for microwave shielding effectiveness requires a shielding enclosure, a cavity made from the test material. A receiving antenna is placed in the cavity, which then measures the power transmitted into the interior of the box from a power source on the exterior. This test procedure has not been modified for cryogenic measurements due to the difficulty in cooling the entire cavity in liquid nitrogen.

III. WAVEGUIDE FIXTURE AND MEASURING TECHNIQUE

The new waveguide fixture operates by the same basic "insertion loss" principle as the NIST coaxial device.[6] The specific fixture has two coaxial to X-band waveguide adapters operating in the 7.5–12.5 GHz frequency range (Fig. 1). A sample is placed between the two waveguide adapters, which are then bolted together with nylon screws and connected to an Hewlett Packard HP8510B Network Analyzer via 50 Ω coaxial cables to determine what fraction of the source energy is transmitted through a sample. The network analyzer serves as both the source and detector of electromagnetic radiation. Measurements are typically taken at 0.05 GHz intervals. At each frequency, 32 input–output data pairs are collected and averaged. Shielding effectiveness (SE) is then calculated using the following equation:

$$\mathrm{SE}=10*\log(P_{\mathrm{in}}/P_{\mathrm{out}}),$$

where P_{in} is the incident (transmitted) power, and P_{out} is the transmitted (received) power, and SE is reported in decibels (dB). A portion of the shielding effectiveness accounts for the non-normal incident power associated with waveguides. With additional manipulation of the data to account for slight shifts in the angular incidence, this portion, approximately 3 dB, of the shielding effectiveness may be removed if desired.

Because the waveguide fixture is immersed in liquid nitrogen for cryogenic measurements, it has been modified by drilling small holes at the current nulls on the top and bottom of each waveguide adapter. The holes permit liquid nitrogen to flow freely through the fixture and contact the test sample without disturbing the electromagnetic field distribution in the adapters. The inner dimensions of commercially available waveguides are specifically designed assuming that air will be the transmission media. No direct modifications are made to the fixture to account for the differences introduced by the presence of liquid nitrogen. However, in order to eliminate any errors this may introduce, calibration of the modified waveguide fixture is performed while the fixture is immersed in liquid nitrogen. The calibration process, Thru-Reflect-Line (TRL), is able to remove errors due to the use of a liquid nitrogen dielectric as well as those from the microwave adapters, making all subsequent measurements necessarily relative to the calibration standards. The calibration standards used were a Thru, a shorting aluminum plate (Reflect), and a 7.5 cm section of waveguide (Line). The maximum shielding effectiveness that can be measured for the system dynamic range is ~90 dB at room temperature and ~80 dB at liquid nitrogen temperatures. In other words, this device can distinguish between samples that shield up to 99.999 999% of the electromagnetic field. This is not a severe limitation, because distinguishing between materials that shield above 80 dB is not of practical significance. All materials that shield above this level would be considered excellent shields.

IV. VERIFICATION OF MEASUREMENT DEVICE

Several materials were measured to verify the validity of the measurement technique to compare shielding effectiveness of materials. Figure 2 compares four of these materials—copper, steel, carbon filled polymer, and Teflon. The copper was cut from a commercially available copper sheet that was 0.61-mm thick and the steel was 0.3-mm thick shim stock from ARCO Corporation. The 1.95-mm thick carbon filled composite was a DuPont Kalrez, a composite with 11.9 vol. % carbon black in perfluoroelastomer. The DuPont Teflon sample was a 0.5-mm sheet. Copper is a very good conductor that is expected to shield very well in the microwave frequency range. It should perform as well as the calibration standard, aluminum. The conductivity of steel is lower than that of aluminum or copper; therefore, it is expected to shield less effectively than either aluminum or copper. The conductivity of the carbon composite is very low, but nonzero, $[1.18\times10^{-10}\ (\Omega\ \mathrm{cm})^{-1}]$, therefore it should attenuate the field only a small amount. And Teflon is a nonconductive polymer that should not

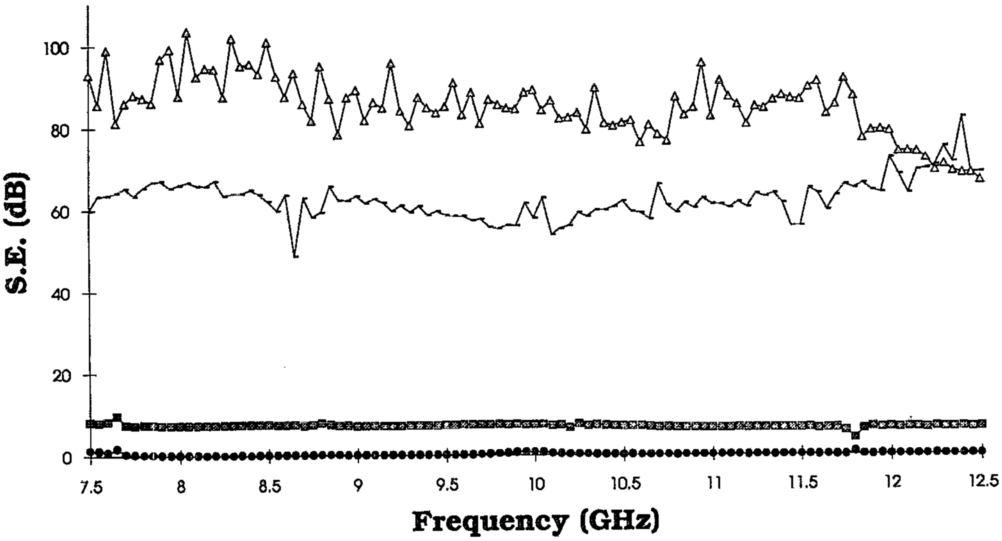

FIG. 2. Shielding effectiveness vs frequency for copper (▲), steel (□), carbon filled elastomer (■), and Teflon (●) at room temperature.

shield at all. The expected results were obtained during room temperature measurements, as shown in Fig. 2. The shielding effectiveness reported at each frequency represents the average of 32 data points. The precision of the data is ± 5 dB. The copper sheet has a shielding effectiveness between 80 and 90 dB which is the limit of the calibration. Steel shim stock has a shielding effectiveness of ~ 65 dB, which is slightly lower than copper, as expected. The shielding effectiveness of the carbon filled composite was ~ 8 dB, while the nonconductor, Teflon, has a shielding effectiveness less than 1 dB. The shielding effectiveness of each sample was determined using both nylon and metal screws to hold the waveguide fixture together to determine if the type of screw connection affected the results. Figure 3 shows that the shielding effectiveness for the carbon filled composite is independent of the type of screw attachment. This is the most lossy material; therefore, if the type of screw, conducting or insulating, had an effect, we would expect to see it with this material. However, as with all the materials, the shielding effectiveness was the same for both tests. After recalibrating the device in liquid nitrogen, these four samples were characterized at cryogenic temperatures. The results were the same, with the exception of those for the copper sample. As shown in Fig. 4, the shielding effectiveness of copper was ~ 10 dB lower than that measured at room temperature. However, since copper is an excellent shield at microwave frequencies, measurements on copper at both temperatures are limited by the sensitivity of the device.

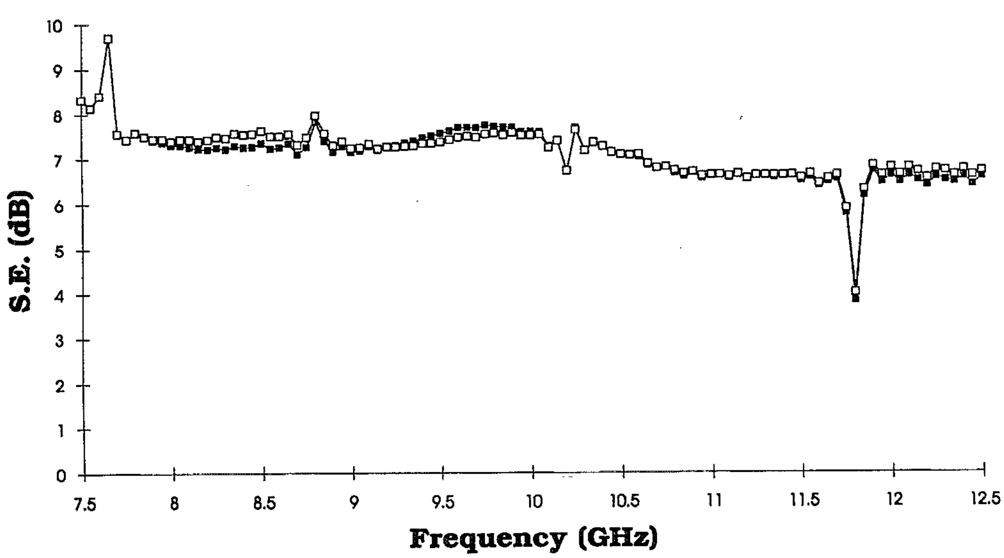

FIG. 3. Shielding effectiveness vs frequency for carbon filled elastomer with nylon screw connectors (■) and metal screw connectors (□) at room temperature.

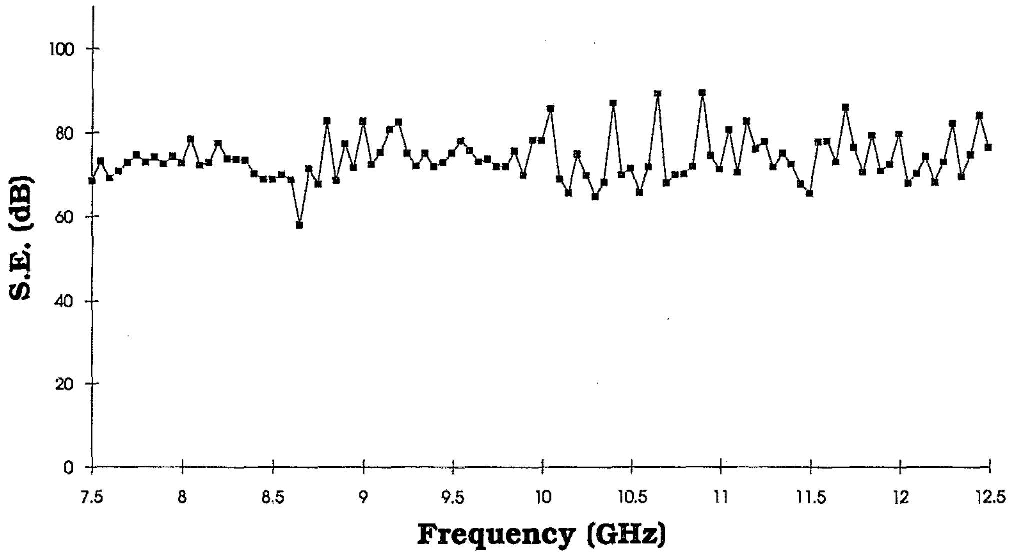

FIG. 4. Shielding effectiveness vs frequency for copper (▲) and YBCO (□) in liquid nitrogen.

V. DATA

Once verifying that the waveguide device could be used to compare shielding effectiveness of materials, with varying electromagnetic properties, materials that have interesting properties in the desired temperature and frequency ranges could be analyzed. For example, the shielding effectiveness of a high temperature superconductor, $YBa_2Cu_3O_{7-x}$ (YBCO), was measured. The 2.4-mm disk was made by sintering 2–6 μm YBCO powder supplied by the Seattle Superconductor Company. The shielding effectiveness of the YBCO disk, shown in Fig. 4, is between 70 and 80 dB, which is the limit of the device in liquid nitrogen. This was verified using several YBCO disks with varying thicknesses. YBCO is therefore a very good shield at liquid nitrogen temperatures and microwave frequencies.

ACKNOWLEDGMENT

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