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High Power Intermodulation Measurements up to 30 W of High Temperature Superconducting Filters

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Abstract We have demonstrated a high power intermodulation measurement set-up capable of delivering 30 W in each of two fundamental tones. For closely spaced frequencies (< 35 MHz), the dynamic range of the measurement is limited by the nonlinear performance of the mixer in the front end of the HP71210C spectrum analyzer. A tunable TE_{011} mode copper cavity was fabricated in which one of the endwalls could be adjusted shifting its resonant frequency between 5.7 and 6.6 GHz. Since the Q-value of this cavity is high, > 10^4, and its bandwidth is small, < 1 MHz, it can be used to attenuate the two fundamental tones relative to one of the harmonic tones, which greatly enhances the dynamic range of the measurement. This set-up can be used to measure the two-tone intermodulation distortion of any passive microwave device, e.g. a HTS filter, a connector, a cable, etc., over a frequency range of 5.9 to 6.4 GHz and a power range of 0.1 to 30 W. The third order intercept (TOI) of a prototype HTS filter measured at powers up to 30 W was +81.3 dBm.

I. Introduction

The discovery of high-temperature superconducting (HTS) materials that operate at or above liquid nitrogen temperature opens the possibility for a new class of high performance microwave cryoelectronics.[1] The surface resistance (R_s) of a HTS material can be 50 times lower than copper when both are measured at 77 K and 10 GHz. The superior electrical performance of HTS materials can be used to produce passive microwave devices, e.g. filters, delay lines, splitter/combiners, etc., with performance superior to conventional devices. In addition, the performance of many semiconductor devices may also be improved when cooled to cryogenic temperatures. High temperature superconductors, however, are nonlinear materials and so some superconducting devices show superior performance only at low microwave power. The drastic performance degradation at high power is in fact one of the main factors limiting the use of HTS materials in many cryoelectronic applications. It is thus important to be able to characterize the nonlinear performance of HTS components at high power levels.

The surface resistance of any superconductor will become nonlinear with respect to an applied field when the rf surface magnetic field exceeds the critical field for flux penetration of the rf field into the superconductor.[2] However, even at field values below the critical field, the surface resistance of the superconductor is nonlinear because the applied field modifies the densities of the superconducting and normal electrons, an effect which can be modeled using Ginsburg-Landau theory.[3] In essence,

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the local density of superconducting electrons (and so the local surface resistance) depends upon the local surface magnetic field or equivalently, the local current density. This nonlinearity of the surface resistance is what leads to the generation of new harmonically related frequencies.

Many types of nonlinearities may be considered in the design of a microwave system. One type is intermodulation, the generation of linear combinations of two or more excitation tones. Another type is harmonic generation, the generation of integer multiples of a single excitation tone. A third type is saturation and desensitization, the distortion of a small tone when a large tone drives a circuit into saturation. A fourth type is cross modulation, the transfer of modulation from one tone to another. A fifth type is AM/PM conversion, the conversion of amplitude changes into phase changes. Superficially, at the system level, these are often considered to be separate phenomena, but they are simply different manifestations of the same nonlinearity.

The two-tone intermodulation measurement is a common specification for many microwave systems, especially in communications. Two closely spaced separate tones, frequencies ω_1 and ω_2, are combined to drive a device under test, DUT. The nonlinearity transfers power to the intermodulated frequencies, for example, $\omega_1 - \omega_2$ and $\omega_1 + \omega_2$, for the second order intermodulation; $3\,\omega_1$, $2\,\omega_1 - \omega_2$, $2\,\omega_2 - \omega_1$ and $3\,\omega_2$ for the third order intermodulation, etc.. The power level of the fundamental tones is measured at the input of the DUT. The power level of the fundamental and intermodulated tones is measured at the output of the DUT. A log-log plot of the input power versus the output power should yield a straight line of slope 1 for the fundamental tones, slope 2 for the 2nd order intermodulated tones, slope 3 for the 3rd order intermodulated tones, etc. When the nonlinear distortion is small, the straight line for the fundamental tones has an intercept of zero. The straight line for a 2nd order intermodulated tone should have a slope of 2, and can be summarized by a single number, the second order intercept (SOI). Similarly, the 3rd order intermodulated tones should a slope of 3, and can be summarized by a single number, the third order intercept (TOI).

HTS thin film materials have a very low surface resistance and therefore a very high Q-value which can be used to produce very small, planar microwave filters with low in-band insertion loss, steep skirts and high off-band rejection.[1] Using traditional design approaches, HTS filters with excellent microwave properties have been demonstrated but only when operating at low power levels, < 1 W, insufficient for most transmit applications. A new and novel approach was used to design a high power HTS 6 GHz, 1.3 % equi-ripple bandwidth, 3-pole TM_{01} mode filter.[4] The greatly improved power handling characteristics (> 100 W) of this filter requires a high power intermodulation measurement.

II. Experimental

A schematic representation of the high power intermodulation set-up is shown in Figure 1. Each synthesized source generates a single fundamental tone that is feed to a high power solid state amplifier capable of delivering up to 150 W between 5850 and 6425 MHz. The output power of each amplifier is monitored with a power meter and after calibration, is used to calculate the input power of each fundamental tone delivered to the device under test (DUT). Each high power tone is then filtered and combined in a 3 dB hybrid coupler. Half of the power of the combined tones is absorbed by a high power load but the remaining power, up to 30 W in each fundamental tone, is delivered to the DUT. The nonlinear response is measured with a spectrum analyzer and after calibration, is used to calculate the output power of each of the fundamental and intermodulation tones produced by the DUT.

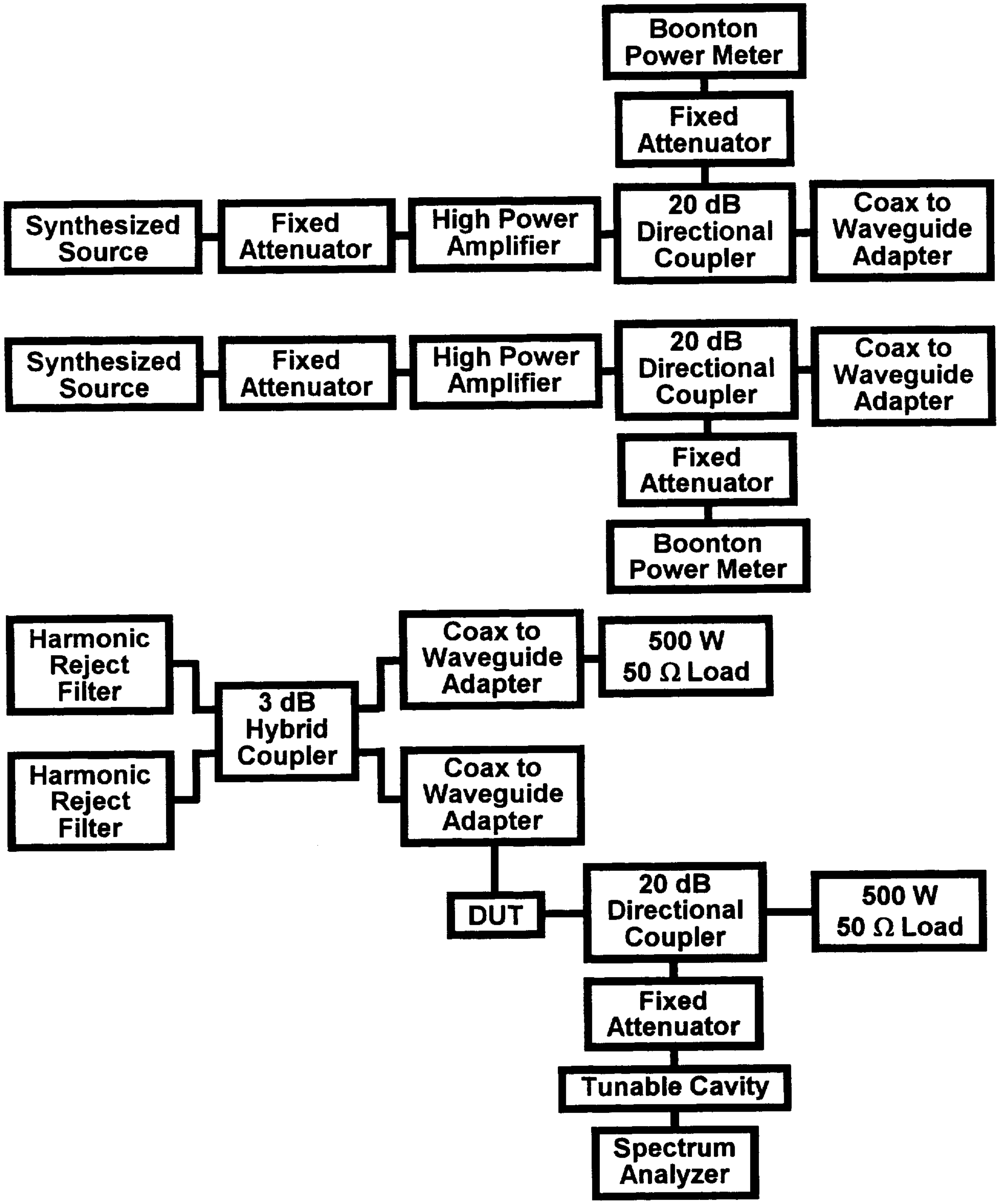

Figure 1 A schematic representation of the high power intermodulation set-up.

A. Instrumentation

HP83640A and HP8341B Synthesized Sources These instruments supply the fundamental tones for channel 1 and 2, respectively. Each source outputs a single tone with a frequency of between 5.8 and 6.5 GHz with 1 Hz resolution. The power level of this tone can vary between -20 and +10 dBm with .01 dBm resolution for the HP83640A and between -10 and +20 dBm with .05 dBm resolution for the HP8341B. Each 10 MHz reference is locked to the 10 MHz reference of the spectrum analyzer. The RF output is connected to the RF input of a high power amplifier.

MAXTECH PCD 6350/R and 6150/R Amplifiers These instruments amplify the fundamental tone for channel 1 and 2, respectively. Each single tone is amplified to a maximum power of approximately 150 W. These amplifier have a large gain, 90 dB and 65 dB respectively, and thus it is important to limit their input power by inserting the appropriate attenuation. It is also important to note that this amplifier is a non-linear device and generates harmonics that will limit the sensitivity of the measurement. The RF input of each amplifier is connected to a synthesized source and the RF output is connect to the input of the source 1 or 2 coupler.

Boonton Power Meter This instrument monitors the output power of both of the solid state amplifiers. The input power delivered to the DUT can be calculated from these measurements by using the passive calibration of the hybrid network. The power handling limitation of the sensors is +25 dBm (300 mW) and thus it is important to limit the power by inserting the appropriate attenuation. The channel 1 and 2 sensors of the Boonton Power Meter are connected to the coupler port of the source 1 and 2 couplers, respectively.

HP71210C Spectrum Analyzer with Z40 This instrument measures the power in the fundamental and harmonic tones at the output of the DUT. The power handling limitation of this instrument is +30 dBm (1 W) and thus it is important to limit the power by inserting the appropriate attenuation. The input to the spectrum analyzer is connected to either the output of the output coupler or to the tunable cavity.

B. Components

Fixed Attenuators NARDA model 4782 SMA miniature fixed attenuators are used to limit the input power delivered to the high power amplifiers, the power sensors and the spectrum analyzer. They operate over a frequency range of DC to 18 GHz; can handle an average power of 2 W and a peak power of 200 W; and have a VSWR of less than 1.3 between 4 and 12.4 GHz.

Directional Couplers NARDA model 3004-20 type N coaxial direction couplers are used to monitor the input and output power levels to the DUT. They operate over a frequency range of 4-10 GHz; have a directivity of 20 dB from 4-8 GHz; have an total insertion loss of .25 dB (including the coupling loss); have a VSWR of less than 1.20 dB; and can handle an average power of 500 W and a peak power of 10 kW.

Coax to Waveguide Adapters MDL model 137AC116-1F adapters are used to convert between type N coaxial and WR137 waveguide components. They operate over a frequency range of 5.85 to 8.20 GHz; have a VSWR less than 1.065; and can handle an average power of 1 kW.

Harmonic Reject Filter MDL Model 137FL16137FL16 lowpass waveguide (harmonic reject) filters are used to attenuate the harmonic frequencies generated by the high power amplifiers. They operate with a passband of 5.925 to 7.125 GHz; have a passband insertion loss of less than 0.3 dB; have a VSWR of less than 1.15 dB; reject the 2nd harmonic by more than 40 dB; reject the 3rd harmonic by more than 30 dB; and can handle an average power of 2 kW.

3 dB Hybrid Coupler MDL Model 137HS72 3 dB hybrid coupler is used to combine the two high power fundamental tones. A hybrid coupler was chosen because the high isolation between the two input ports limits the harmonic distortion generated in the output isolators of the high power amplifiers. Unfortunately, the combined tones appear equally at each of its two output ports and thus only half of the high power is delivered to the DUT. It operates over a frequency range of 5.8 to 6.5 GHz; has an isolation of > 18 dB; and can handle an average power of 3 kW.

500 W 50 □ Loads NARDA Model 368BNM 50 □ loads absorb the high power microwave energy at one of the outputs of the 3 dB hybrid coupler and at the output directional coupler preventing unwanted reflections. They operate over a frequency range of 2 to 18 GHz; can handle an average power of 500 W and a peak power of 5 kW; and has a VSWR of < 1.45.

Tunable Cavity The tunable cavity was designed and fabricated in-house. It is a TE_{011} mode copper cylindrical cavity where the position of one of the endwalls can be adjusted using a micrometer thus shifting the resonant frequency between 5.7 and 6.6 GHz, see Figure 2. Since the Q-value of this cavity is high, > 10^4, and its bandwidth is small, < 1 MHz, it can be used to attenuate the two fundamental tones relative to one of the intermodulation tones. For example, for two closely spaced fundamental tones (7 MHz), the chosen harmonic is attenuated 4 dB while the two fundamentals are attenuated by > 20 dB and > 35 dB. This should improve the dynamic range of the measurement by more than 30 dB.

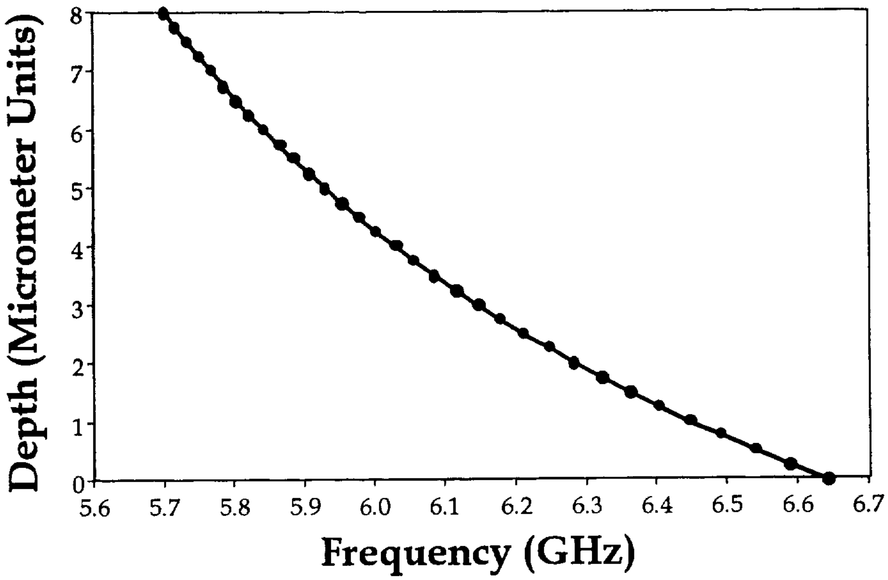

Figure 2 The frequency response of the tunable cavity as a function of the position of the endwall.

C. System Performance and Calibration

In most intermodulation measurements, the nonlinear distortion to be characterized is small, thus the dynamic range of a spectrum analyzer for combinations of closely spaced large and small tones may be a severe limitation.[5] The dynamic range of an intermodulation measurement in this experimental set-up is limited by the nonlinearity introduced by the front end mixer in the spectrum analyzer, in this case, a HP71210C. For broadly spaced frequencies, the pre-selection filter, BW 35 MHz, attenuates the large fundamental tones and only the small intermodulation tones are present at the mixer. In this case, the dynamic range of the measurement approaches that of the receiver noise floor of the spectrum analyzer, ~120 dB. For closely spaced frequencies, the pre-selection filter does not attenuate the unwanted signals and both the large fundamental tones as well as the small intermodulation tones are present at the mixer. In this case, the dynamic range approaches that of the D/A converter of the spectrum analyzer, ~80 dB.

A two-tone intermodulation measurement compares the power levels of the fundamental tones delivered to and intermodulation tones generated by the DUT. In the experimental set-up shown in figure 1, power levels are measured by either the power meter or the spectrum analyzer. If the passive loss characteristics of the hybrid network are measured, then the power levels at the input and output of the DUT can be calculated.

A procedure was developed to calibrate the instrumentation and the passive hybrid network. The S-parameters of the two source directional couplers were measured on a network analyzer and recorded. The insertion loss of the input and output cables for the DUT were also measured on a network analyzer and recorded. The spectrum analyzer and power meter were calibrated using their internal calibrators. Using a pure tone generated by either synthesized source at the measurement frequency, the absolute power level measured by the spectrum analyzer was adjusted by setting the amplitude reference offset such it agreed with the power meter. The measurement set-up was then assembled without the DUT and without the tunable cavity. The input and output power levels were measured for all of the fundamental and harmonic frequencies. This data was used to calculate the insertion loss of the hybrid network and the noise floor of the solid state amplifiers. Finally, the tunable cavity was inserted into the measurement set-up. One of the synthesized sources was set to the desired harmonic frequency and the insertion loss of the cavity was minimized. The input and output power levels were measured for all of the fundamental and harmonic frequencies. This data was used to calculate the insertion loss of the tunable cavity.

Once the instrumentation and the hybrid network had been calibrated, the two-tone intermodulation measurement could be made. The power level of each synthesized source was set to its minimum value. Each fundamental tone was activated separately and the power level at the input of the DUT was measured. The power levels of the two tones were matched by adjusting the power level of either of the synthesized sources. Both fundamental tones were then presented to the DUT and the output power levels were measured for the fundamental and harmonic frequencies by the spectrum analyzer. The power level was increased by 1 dB and the nonlinear performance re-measured.

The measurement system was assembled without the tunable cavity or a DUT. The nonlinear performance of the measurement system for two closely spaced fundamental tones (7 MHz) is shown in Figure 3. The measurement system itself shows a significant intermodulation distortion with a TOI of +82 dBm, or equivalently, a 3rd order intermodulation distortion of -75 dBc at an input power level of 30 W. This nonlinear response is dominated by the mixer in the front end of the spectrum analyzer. The tunable cavity was inserted into the measurement system and the nonlinear performance is also shown in Figure 3. The tunable cavity attenuated the fundamental tones 25 dB more than the harmonic tone. The measurement system showed a significant improvement of the intermodulation distortion with a TOI of +95 dBm, or equivalently, a 3rd order intermodulation distortion of -100 dBc at an input power level of 30 W.

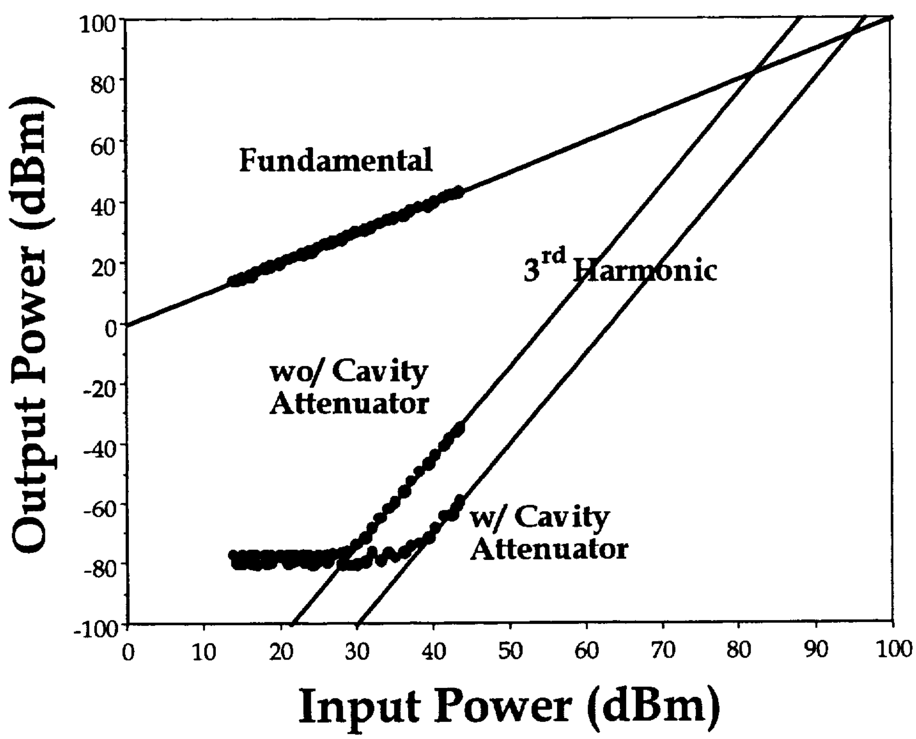

Figure 3 The nonlinear performance of the high power intermodulation measurement set-up for two closely spaced fundamental tones (7 MHz). Without the tunable cavity, the TOI was +82 dBm, or equivalently, the 3rd order intermodulation was -75 dBc at 30 W. With the tunable cavity, the TOI was +95 dBm, or equivalently, the 3rd order intermodulation was -100 dBc at 30 W. The slope of the fundamental and 3rd harmonic fits are 1 and 3, respectively.

IV. Filter Design

Several design innovations were explored to extend the power handling of HTS planar filters.[4] Sonnet Electromagnetic Analysis Software was used to design the filter. A frequency sweep covering the pass-band was used to calculate the S-parameters and the peak current. The maximum current was used as the criteria to optimize the power handling of the filter design. The final design of a high power 6 GHz, 1.3% equi-ripple bandwidth, 3-pole TM_{01} mode filter is shown in Figure 4.

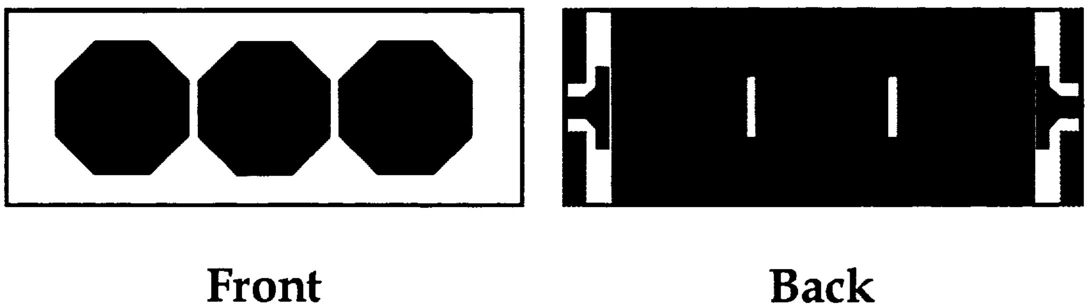

Figure 4 A layout of a high power HTS 6 GHz, 1.3 % equi-ripple bandwidth, 3-pole TM_{01} mode filter. The circuit was fabricated using a double sided $Tl_2Ba_2CaCu_2O_8$ HTS on 20-mil thick 41 mm x 17 mm $LaAlO_3$ substrate.

V. Results

A high power HTS 6 GHz, 1.3% equi-ripple bandwidth, 3-pole TM_{01} mode filter was fabricated using a double sided $Tl_2Ba_2CaCu_2O_8$ HTS on 20-mil thick $LaAlO_3$ substrate. The S-parameter performance was measured using a high power network analyzer.[6] The two-tone intermodulation performance is shown in Figure 5. The TOI of the measurement system was +95 dBm, or equivalently, the 3rd order intermodulation distortion was -100 dBc at an input power level of 30 W. The TOI of the HTS filter was +81.3 dBm, or equivalently, the 3rd order intermodulation distortion was -73 dBc at an input power level of 30 W.

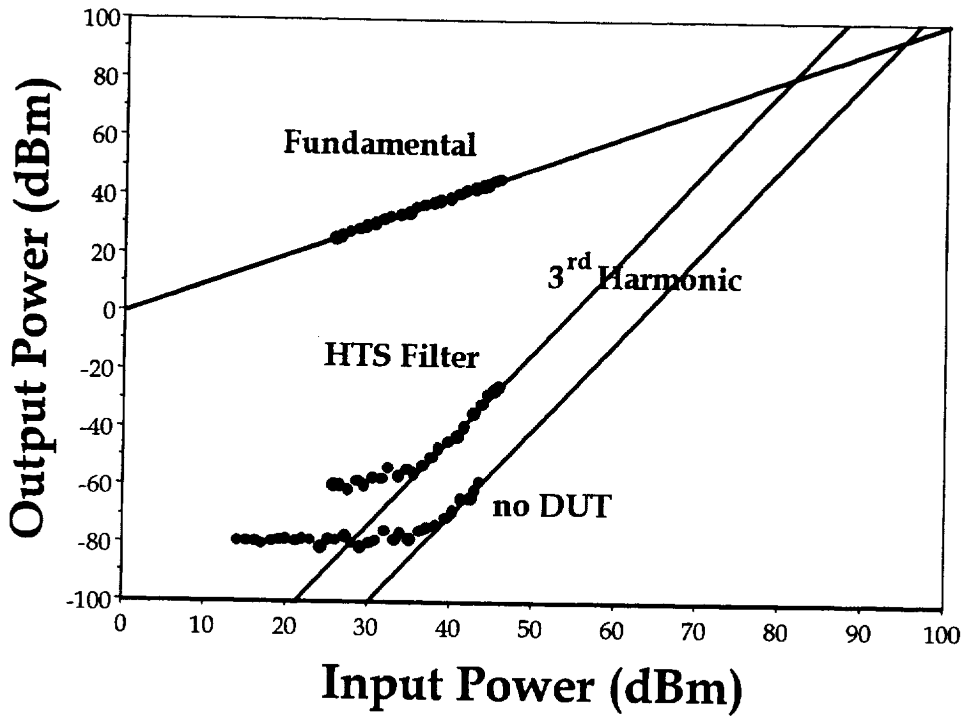

Figure 5 The high power intermodulation performance of a HTS 6 GHz, 1.3 % equi-ripple bandwidth, 3-pole TM_{01} mode filter. The slope of the fundamental and 3rd harmonic fits are 1 and 3, respectively.

VI. Conclusions

We have demonstrated a high power intermodulation measurement set-up that can be used to measure the two-tone intermodulation distortion of any passive microwave device, e.g. a HTS filter, a connector, a cable, etc., over a frequency range of 5.9 to 6.4 GHz and a power range of .1 to 30 W. For closely spaced frequencies, < 35 MHz, a tunable TE_{011} mode copper cavity was used to improve the dynamic range of the measurement. The HTS filter which can operate at +50 dBm (100 W) CW had a predicted intermodulation of better than -60 dBc, acceptable for most transmit applications.

VII. Acknowledgments

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