VECTOR MEASUREMENTS OF MICROWAVE DEVICES AT CRYOGENIC TEMPERATURES

J.W. Smuk, M.G. Stubbs and J.S. Wight*

Communications Research Centre, Ottawa, Ontario, Canada
*Dept. of Electronics, Carleton University, Ottawa, Ontario, Canada

ABSTRACT

A real-time method to de-embed S-parameter measurements of MIC devices operated at 77°K is presented. Measurements of both an interdigitated capacitor and a GaAs MESFET cooled in a liquid nitrogen bath are shown for frequencies from 2.5 GHz to 20 GHz.

INTRODUCTION

This paper describes the first reported method to de-embed, in real-time, broadband vector measurements of MIC devices operated at cryogenic temperatures. An apparatus to immerse the devices into liquid nitrogen and microstrip jigs that survive the extreme temperature drop were constructed in order to apply the Through-Reflect-Line (TRL) calibration technique to measurements over a frequency band from 2.5 GHz to 20 GHz.

Although only conventional MIC devices are measured in this paper, the main application foreseen will be the characterization of MICs utilizing a combination of conventional semiconductor technology and high temperature superconductor technology. Once cooled to liquid nitrogen temperatures, these hybrid semiconductor /superconductor MICs should allow highly reliable low-noise amplifiers, oscillators and mixers to be designed (1).

MEASUREMENT APPARATUS AND TECHNIQUE

The microwave devices, mounted on jigs, are cooled to 77°K using a dipping technique in which a cold finger attached to the jig is slowly immersed in liquid nitrogen. Figure 1 illustrates the apparatus in which a Hewlett Packard 8510B automatic network analyzer is connected to a microwave jig using K-cables. The cables and jig are stationary while the cryoflask is raised to cool the device.

The TRL technique (2) is used to calibrate the network analyzer at 77°K. This allows the effects of the jig's microstrip transmission lines and K-connectors as well as the interconnecting cables to be mathematically removed, resulting in real-time de-embedded measurements. Only the minor effect of the wire bonds connecting the device remain to be stripped. Note that the phase and amplitude errors caused by the characteristics of the cables and jigs changing with temperature are inherently corrected by using this technique. This is unlike previous methods (3,4) which used low thermal conductivity, microminiature coaxial cable to absorb the thermal gradient over a short distance and either ignored or manually de-embedded the errors caused by the large temperature change.

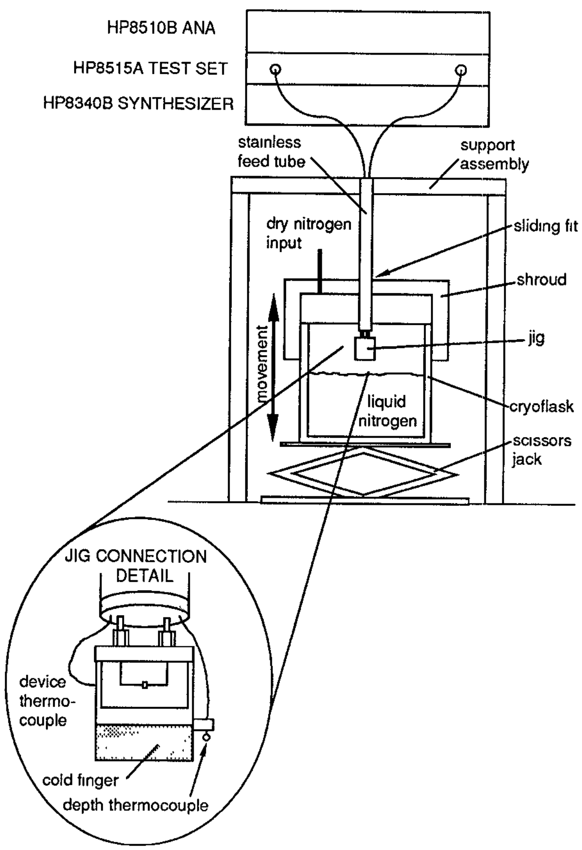

Figure 1. Experimental Apparatus.

A TRL measurement requires through, reflect and line standards for calibration as well as a jig for device mounting. Although the TRL technique assumes that the connectors and microstrip I/O lines on every standard and device jig are identical (5), separate jigs for each standard and measured device are used in this experiment in order to ensure repeatable connections at 77°K. Since the connectors and I/O lines on the different jigs are not identical, the usual TRL accuracy obtained with split-block jigs at room temperature is reduced.

Microstrip transmission lines patterned on 0.010" alumina form the standards as well as the I/O lines of the measurement jigs. The standards used to provide a calibration from 2.5 GHz to 20 GHz include a zero length through, an open (the reflection standard) whose gap corresponds to the space occupied by the device and a line 0.101" longer than the through. The MIC devices are wire-bonded onto 0.020" and 0.050" wide ridges on the measurement jigs. A complete set of standards and two measurement jigs are shown in Figure 2. To ensure phase and amplitude accuracy, the microstrip lines and launcher recesses are kept to a tolerance of 0.001". Both the alumina and the centre pins of the spark plug launchers are attached using Indium/Lead solder to ensure a solid connection at 77°K.

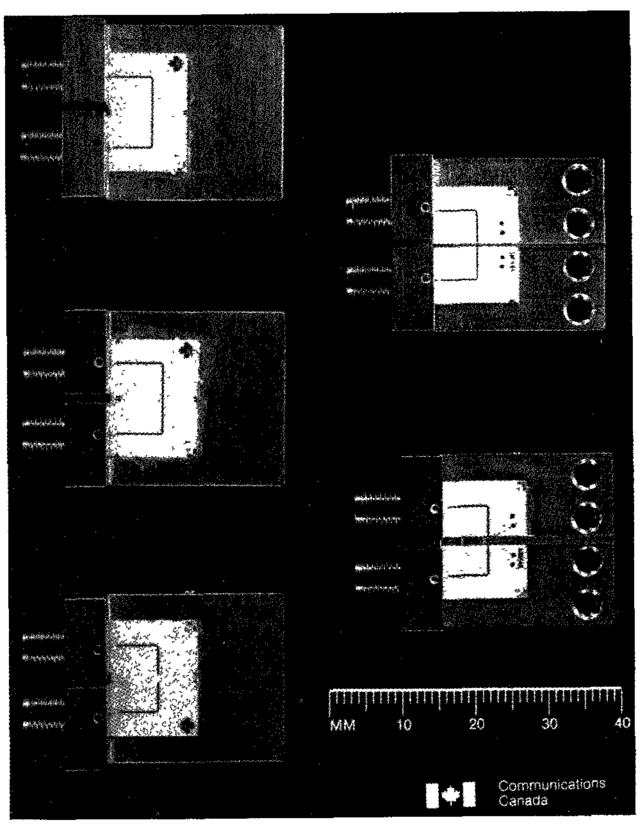

Figure 2. Microwave Jigs - Counterclockwise from top left - Through, Line, Open, measurement jig with an interdigitated capacitor, measurement jig with a Gould 0503 MESFET.

To perform a 77°K TRL measurement, the cryoflask was slowly raised to immerse the cold finger in liquid nitrogen. Copper-constantan thermocouples mounted on the jig allowed the temperature of the system to be maintained by controlling the immersion depth to within 1 mm. Thermocouples mounted on the K-cables inside the stainless steel feed tube were used to monitor the thermal properties of the system. Approximately 45 minutes after immersion, the system reached thermal and electrical equilibrium allowing a measurement to be taken. To change the jig, the flask was lowered and a heater warmed the jig to room temperature after an additional 45 minutes. The three standards and the measurement jig were thermally cycled using this method resulting in a calibration requiring 6 hours and device measurements requiring an additional 2 hours each.

RESULTS AND INTERPRETATION

Since the standards and device to be measured are mounted on different jigs, measuring the same standards used to calibrate does not reflect the true accuracy of this method because they are defined by the calibration kit to be ideal. Therefore, to determine the accuracy expected when attaching the measurement jig, other sets of "identical" standards were measured following the calibration.

The results of measuring "identical" through standards mounted on different jigs over the 2.5 GHz to 20 GHz band and following calibrations at both 77°K and 300°K are shown in Table 1. Typical deviations of the standards from an ideal through ($S_{21} = 1\angle 0°$, $S_{11} = S_{22} = 0$) are shown for both the reconnected calibration standard as well as different standards. Since the $|S_{21}|$ deviations were random and centred about 0 dB, they are quoted in peak-to-peak units whereas the $\angle S_{21}$ deviations were found to increase linearly with frequency and the values quoted are the 20 GHz errors. The "Calibration Standard" data is included to show the accuracy possible using a perfect split-block jig which employs identical launchers and I/O lines for all measurements. As a result of using different jigs at 77°K, the return loss is degraded 17 dB while the magnitude and phase errors of S21 increase. A reduction in accuracy at 77°K compared with room temperature is also evident. Since this reduction is minor for the "Different Standard", room temperature measurements may be used to obtain an estimate of the accuracy of this method at cryogenic temperatures. Overall, the accuracy of the transmission measurements is ±0.05 dB in magnitude and a few degrees in angle at 20 GHz.

Table 1 Accuracy of a Through at 300°K and 77°K

	300°K		77°K	
	Calibration Standard	Different Standard	Calibration Standard	Different Standard
Minimum Return Loss (dB)	>50	>25	>40	>23
Δ|S21|(dB)	0.02	0.08	0.06	0.10
Δ∢S21(deg)	0.5	2.0	0.8	3.0

Before discussing the changes in the characteristics of the capacitor and MESFET over temperature, it should be noted that TRL measurements of both devices were verified at 300°K. Both a Cascade Microtech prober and a conventional microstrip jig, which was de-embedded following the measurements, were used.

A 0.5 pF interdigitated capacitor measuring 0.035" x 0.025" and fabricated using a gold thin film deposited on alumina is the first device to be discussed. The input reflections of the capacitor, grounded at one terminal, at 300°K and 77°K are compared in Figure 3. Overall, the capacitor is less lossy at 77°K which agrees with the behaviour of an interdigitated capacitive structure whose ohmic finger resistance has decreased when cooled. The slight counterclockwise phase shift may be caused by a decrease in the capacitance and/or the parasitic series inductance of the cooled capacitor. Note that the effects of the bond wires on these results have not been removed to demonstrate the extent of de-embedding offered by this technique. Conventional manual techniques may be used to strip away these effects.

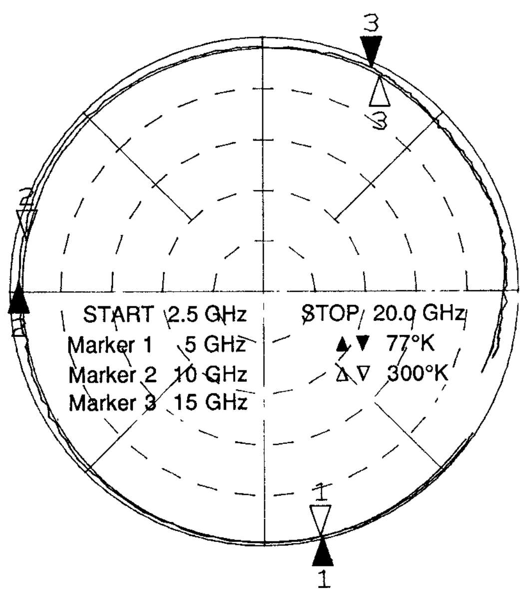

Figure 3. Capacitor Response at 300°K and 77°K.

An unpackaged Gould 0503 0.3 µm x 300 µm Π-gate MESFET was also measured. Both the 77°K and 300°K measurements were made with a 3.5V drain bias and I_{DS}/I_{DSS} ratio of 0.2. The four S-parameters at the two temperatures are plotted in Figure 4. Again, the effects of the bond wires have not been removed. The two S11 curves are almost identical which indicates that the gate-source capacitance is relatively insensitive to temperature. A large increase in |S21| is coupled with a small counterclockwise phase shift at 77°K. This larger magnitude leads to a 1.5 dB increase in the MSG over the entire band. Both S12 curves indicate a reverse isolation of approximately 20 dB and the only difference at the two temperatures is the slightly larger magnitude at 77°K. S22 is smaller in magnitude at 77°K indicating lower drain to source resistance which is expected due to the higher mobility resulting from a reduction in the thermal scattering of the carriers (6). Overall only S22 and S21 appear temperature sensitive which may allow room temperature FET models to be applied at 77°K with only slight modification.

The resonances that appear above 10 GHz are similar to those observed when measuring a "standard" open different from the one used to calibrate. It is believed that these resonances are mainly a result of launcher variation between jigs. More closely matched jigs should extend the resonance free region to higher frequencies.

CONCLUSION

A method to de-embed, in real-time, MIC device measurements at 77°K has been demonstrated. Such a technique should be of use in cryogenic microwave electronics, a field which is expected to grow due to the discovery of superconductors operating at higher temperatures.

Further work is underway to match the jigs more closely in order to extend the resonance free measurement region to higher frequencies.

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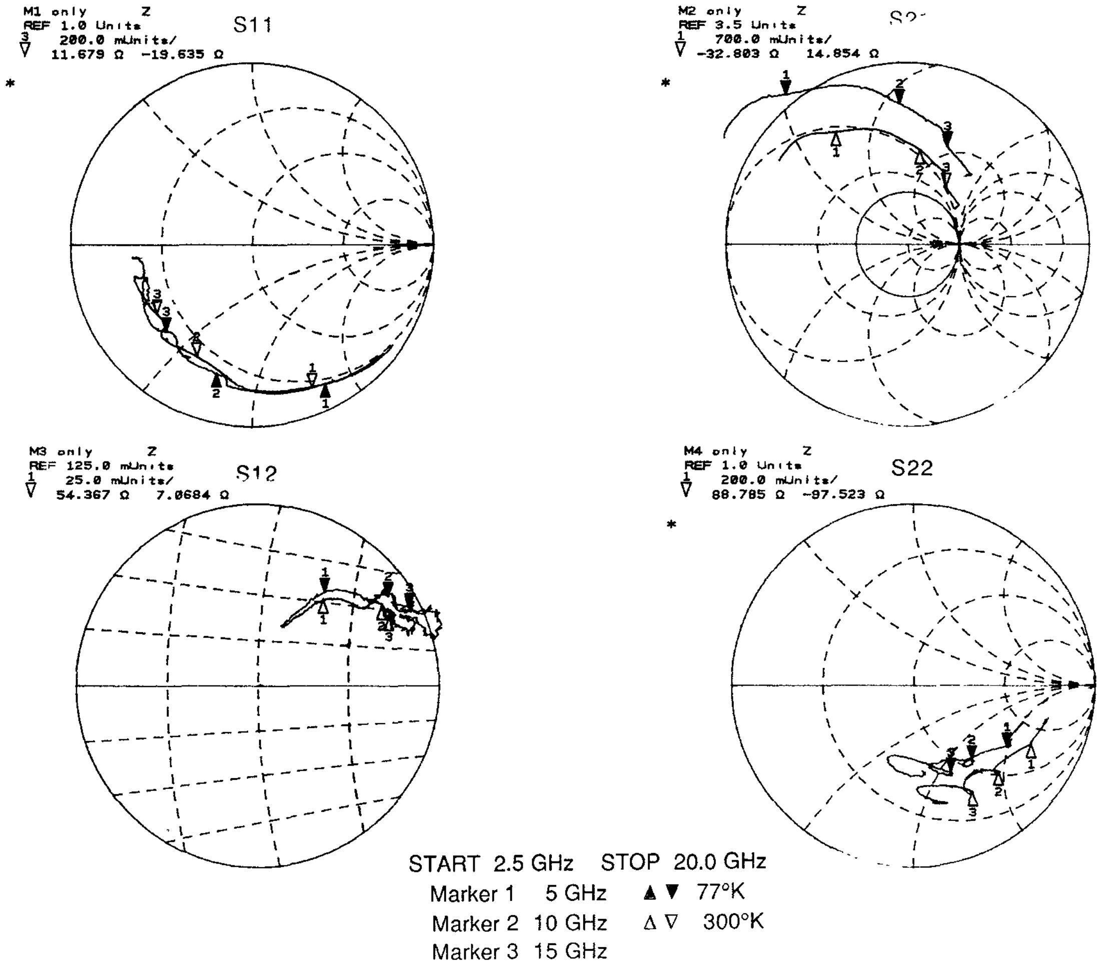

Figure 4. 0503 MESFET Response at 300°K and 77°K.

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