Effect of Temperature and Humidity on a Packaged 5-bit Electrostatically Actuated RF MEMS Phase Shifter

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***Abstract* - RF MEMS 5-bit electrostatic actuated phase shifter die is packaged on FR4 substrate carrier PCB. The RF MEMS phase shifter is subjected to environmental conditions such as temperature, from -40 °C to +85 °C and relative humidity at different temperature levels. The measured S-parameter data are evaluated and compared at different temperature levels of the RF MEMS phase shifter. Empirical formula is extracted based on the measured data for temperature range.**

Keywords: Empirical formula, FR4, Humidity, Temperature, 5-bit RF MEMS Phase shifter

1. INTRODUCTION

Radio Frequency Microelectromechanical Systems (RF MEMS) is more than a decade old and is reaching a mature stage currently, which has generated a tremendous excitement because of its performance enhancement and low manufacturing cost. RF MEMS is a functional device that offers wide applications in space, defense and telecommunications systems. The majority of RF MEMS devices such as phase shifters, switches, resonators, filters, etc. are being made using thin film surface micromachining process. RF MEMS phase shifters are popular for their small size, low weight, wide frequency-band application, low insertion loss and high isolation. Realization of MEMS devices has inherent advantage of simple fabrication process and good mechanical characteristics. However the real application of the device requires working in the natural and harsh environment. Many researchers have done extensive research and published articles on improving the electrical characteristics, insertion loss and isolation loss over the frequency band of the MEMS phase shifters [1,4]. RF MEMS devices used in harsh environment applications typically use low power devices that do not generate much heat to be dissipated to the environment. On the contrary, it is necessary to prevent heat transfer from the environment to the device chip. For this purpose, a low thermal conductivity substrate is most suitable [7]. The lifetime of the MEMS switch is characterized as a function of actuation voltage [2]. The life time improved of the order of a decade for every 5 to 7 V decrease in applied voltage. The capacitive switched switches operate with less than 40 Volts to achieve life time of more than a billion cycles [2]. RF MEMS capacitive switches subjected to different electric fields and humidity levels are explained in [6]. It was found that bulk charging dominates in dry air, while surface charging increases linearly with increasing humidity. Switches made of silicon dioxide are much less susceptible to surface charging than switches made of silicon nitride. There are no experimental data, empirical or theoretical formulae available to predict the reliability and life time of the device in particular environmental conditions. The 5-bit RF MEMS phase shifter is used for experimental purpose. This paper describes the variation of RF parameters of the MEMS phase shifter over the temperature range between -40 °C and +85 °C and humidity at different temperatures. Based on the measurement data, effect of various test conditions on RF parameters were analyzed and empirical formulae were derived for different temperature conditions. The packaging details are explained in Section 2. Experimental results and discussions are described in Section 3, Further work is proposed in Section 4 and conclusions in Section 5.

2. PACKAGING OF 5-BIT RF MEMS PHASE SHIFTER

The fabricated Ku-band, 5-bit MEMS phase shifter is shown in Fig. 1. The 5-bit phase shifter consists of five one-bit phase shifters for 180°, 90°, 45°, 22.5° and 11.25° phase shift, respectively. Each one-bit phase shifter consists of a coplanar waveguide (CPW) transmission line loaded periodically with several shunt MEMS capacitors. The total length and width of the MEMS phase shifter is 13.5 mm and 3.5 mm respectively. The phase shifter was fabricated using Quartz (ε_r =3.8, tan (δ) = 0.001) material. The packaging process consists of preparation of test jig, die attach and wire bonding. Glass protective cap of dimensions 12.43 mm x 2.32 mm x 0.5 mm is cleaned with Iso Propyl alcohol and is placed on the individual phase shifter devices and bonded on the edges with liquid glue to protect the device against environmental conditions. The MEMS die with glass cap is shown in Fig. 2. The Quartz wafer is diced into individual dies using CO_2 Laser dicing machine. The carrier PCB is designed for packaging of the MEMS phase shifter.

The design parameters of CPW transmission line are, width, 80 mil, spacing between signal and ground, 8.1 mil, length, 1320 mil, thickness of the substrate, 64 mil, and FR4 material, ε_r=4.5, was used. Gold plating was used on the carrier PCB. The carrier PCB is shown in Fig. 3.

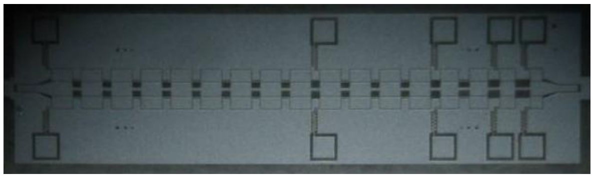


Fig. 1. Fabricated 5-Bit MEMS Phase Shifter

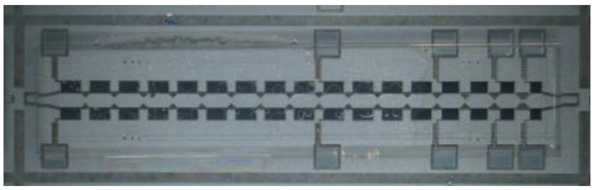


Fig. 2. RF MEMS die with glass cap

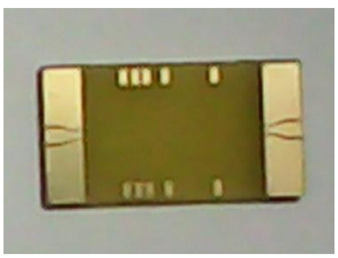


Fig. 3. Fabricated Carrier PCB

2.1 DIE ATTACH

The main function of the die attach is to provide good mechanical attachment of the MEMS structure to the package base. It must survive hot and cold temperature moisture, shock and vibration conditions. The attachment also needs to provide a good thermal path between the MEMS structure base and package. EPO-TEK 353ND epoxy was used to attach MEMS die with FR4 carrier PCB and kept in the oven at 100 °C for 10 minutes duration. Sub Miniature Version A (SMA), connectors (R125.423.200) are connected at both ends of the carrier PCB between the signal line and ground. The CPW transmission signal and ground line on the MEMS die is connected to the carrier PCB signal and ground lines respectively, using wire bonding. Aluminum wire is used for wire bonding at room temperature using HB16, wire bonder machine. Wire bonding is performed using wedge bonding tool to interconnect between MEMS device pads and pads on the carrier PCB, The wire diameter used is 33µm. The parameters set during wedge bonding process are bond time and bond force 300 msec and 310 cNm respectively. Each bit of phase shifter and ground are used for DC actuation voltage. A packaged 5-bit RF MEMS phase shifter is shown in Fig. 4.

Fig. 4. RF MEMS die attach with wire bonding

The circuit can be considered as a synthetic transmission line whose phase velocity can be varied by switching the MEMS capacitive switches up and down. DC control bias for each one-bit phase shifter is connected to the corresponding trace on the FR4 substrate. When a DC bias is applied, the voltage difference between the signal line and ground pad generates a strong electric field underneath the membrane of MEMS switch, which will force the membrane to snap down [7]. This provides a high impedance transmission line when MEMS capacitive switches are at UP states. When switches are snapped down, the transmission line is periodically loaded with MEMS DOWN-state capacitors and will resemble a low impedance transmission line. In this way, a desired phase shift can be achieved without sacrificing too much in return loss. In order to maintain an acceptable matching over a wide band, small DOWN state capacitance value for MEMS switches is required. In the circuit mentioned in [2], the UP state capacitance per period is approximately 5 fF and 0.1 pF DOWN state capacitance value is necessary for good matching. To reduce the DOWN state capacitance value of the single MEMS switch, one possible approach is to use series connected MEMS switch configuration [2].

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The package level measurement was carried out using ZVA24 Vector Network Analyzer. The Network Analyzer is calibrated from 10 MHz to 5.5 GHz using ZU-Z52 Calibration kit. Fig. 5. shows measurement test setup. The measured insertion loss and return loss of the RF MEMS phase shifter at ambient (25° C) is shown in Fig. 6. The measurements were carried out without DC actuation voltage to bit. The insertion loss was better than -5 dB up to 2.0 GHz and more beyond 1.6 GHz. The return loss was better than -18 dB in 1.8 GHz bandwidth. The performance is poor beyond 2.0 GHz and is due to the wire bond length, and mismatch between the device and wire bond length, and between wire bond length and carrier PCB, PCB trace and connector solder junctions. The better performance can be achieved by reducing the wire bond length and proper carrier PCB design. The thermal cyclic chamber Model, C^{1000}, make, WEISS, was used to carry out the measurements from -40 °C to +85 °C. temperature range. The MIL STD 810G specifies the operational low and high temperature are -20 °C and +50 °C respectively [5]. In storage condition, the low and high temperatures, defined in MIL STD [5] are -40 °C and +70 °C respectively. In this work, we have subjected 5-bit RF MEMS phase shifter to a temperature range from -40 °C to +85 °C, and measured insertion loss and return loss parameters. This temperature range includes both operational and storage conditions mentioned in [5].

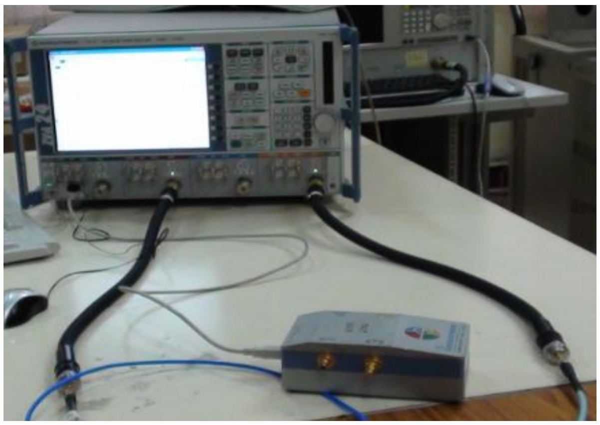


Fig. 5. Measurement Test setup

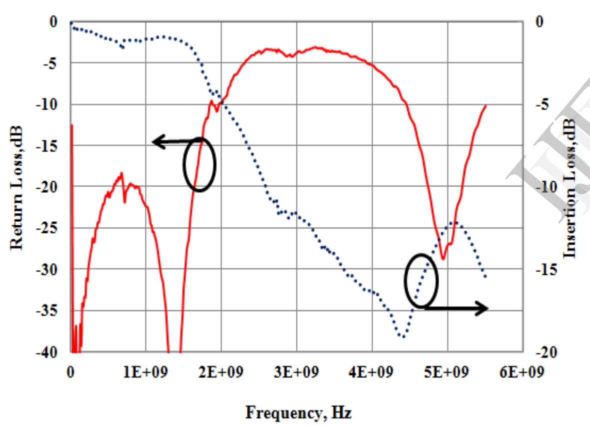
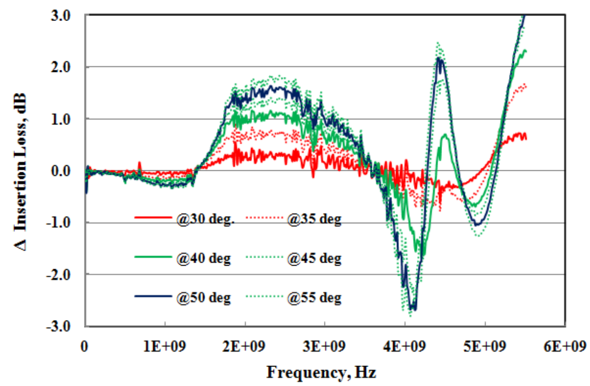


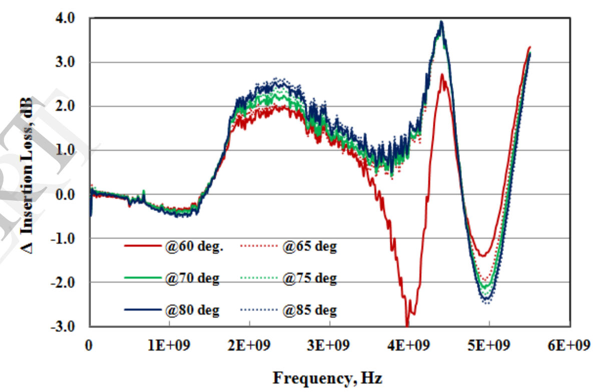
Fig. 6. Measured Return Loss and Insertion Loss of RF MEMS Phase Shifter at 25 °C

3.1 AT HIGH TEMPERATURE

High or Low temperature range is used to evaluate effects of various temperature environment conditions on materials used in RF MEMS devices, packaging and its performance on life cycle. The RF MEMS phase shifter was subjected to high temperature from ambient to +85 °C in the thermal cyclic chamber, the temperature was increased at the rate of 5 °C/min. The insertion loss and return loss were measured at an interval of 5 °C from ambient temperature. Δ IL, dB is the insertion loss w.r.t ambient temperature. The normalized Insertion loss based on the measurements (Δ IL) is shown in Fig. 7. As the temperature increases from the ambient, the insertion loss varies in a cyclic manner. The maximum insertion loss variation was observed around -0.55 dB at +85 °C in the frequency range from 10 MHz - 1.5 GHz. The insertion loss decreased up to 1.5 GHz and started to increase as the temperature increased. The variation is cyclic up to 5.5 GHz frequency range and is shown in Fig. 7.



(a)

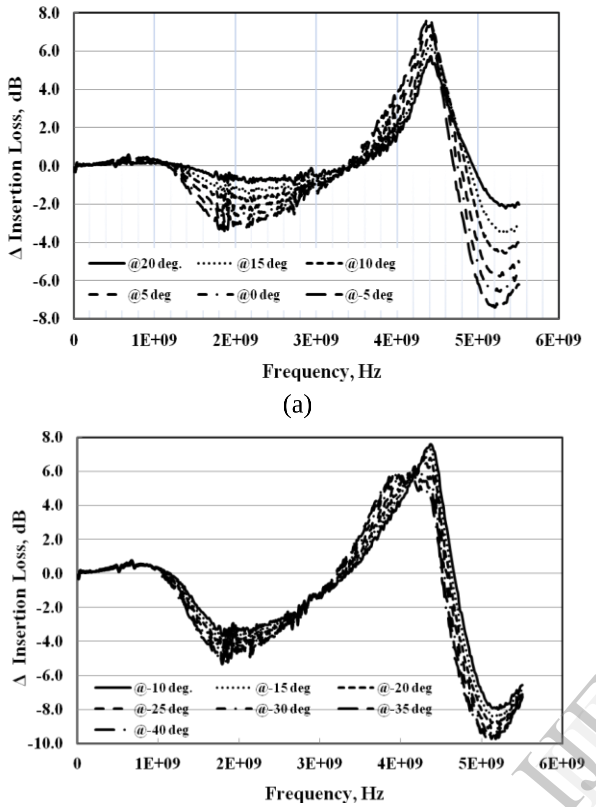


(b)

Fig. 7. Normalized measured insertion loss of RF MEMS Phase Shifter - High Temperature a) from 30 °C to 55 °C b) from 60 °C to 85 °C

3.2 AT LOW TEMPERATURE

The RF MEMS was subjected to low temperature from ambient to -40 °C in the thermal cyclic chamber and the temperature decreased at the rate of 5 °C/min. The insertion loss and return was measured at an interval of 5 °C from ambient temperature. The normalized (with reference to ambient) insertion loss is shown in Fig. 8. The maximum loss variation from ambient to -40° C was 0.8 dB in the frequency band from 10 MHz to 1.5 GHz. From ambient to high temperature, the minimum insertion loss was -0.55 dB and varying in cyclic order as shown in Fig. 9. In 1.5-3.7 GHz frequency band, the insertion loss variation was high compared to 10 MHz - 1.5 GHz band. From +65 °C onwards, no variation found in insertion loss and was constant up to +85 °C. The insertion loss variation at extreme low and high temperature was -8 dB, 4 dB respectively. The measured return loss of RF MEMS shifter from -40 °C to +85 °C temperature is shown in Fig. 10. The measured maximum return loss was better than -4.0 dB from 10 MHz to 5.5 GHz frequency range.



(a)

(b)

Fig. 8. Normalized measured insertion loss of RF MEMS Phase Shifter - Low Temperature a) from 20 °C to -5 °C b) from -10 °C to -40 °C

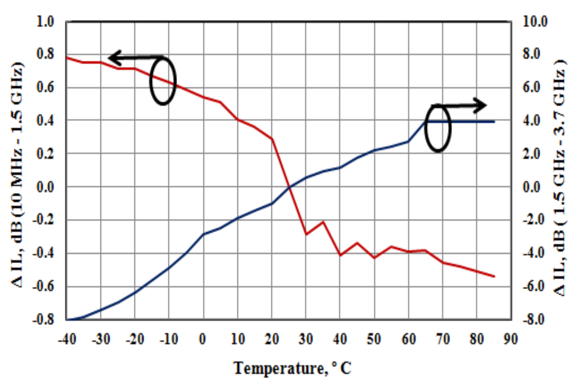


Fig. 9. Normalized Insertion loss (Δ IL, dB) Vs Temperature of RF MEMS Phase Shifter.

The first, second, third resonance frequency of the RF MEMS phase shifter was shifted around 370 MHz, 520 MHz, 320 MHz respectively from extreme low to high temperature is shown in Fig. 10. It may be noted that per °C variation for the first, second and third resonance peak are 2.96 MHz, 4.12 MHz, 2.56 MHz respectively. The performance of the return loss improved by 2 dB as the temperature increase from low to high temperature. An approximate empirical formula for insertion loss for temperature range for two different frequency range were derived based on the measurement data shown in Fig. 9.

Linear and polynomial approximate is considered for frequency range from 10 MHz to 3.7 GHz to extract the empirical formula from the measured data. The contributing factors to improve the performance of RF MEMS phase shifter due to temperature variations over the frequency band are i) performance of material by change in physical dimensions of the material, ii) change in dielectric constant of the material and iii) impedance mismatch between the MEMS device and packaging. For frequency range, 10 MHz - 1.5 GHz, applying, linear approximation, the change in insertion loss,

$$\Delta \text{ IL, dB} = -0.0129 * T + 0.4012 \qquad -40\ °C < T < 85\ °C \qquad (1)$$

Third order Polynomial approximation, for frequency range, 10 MHz - 1.5 GHz

$$\Delta \text{ IL, dB} = 3E\text{-}06 * T^{3} - 0.0002 * T^{2} - 0.016 * T + 0.5062 \qquad -40\ °C < T < 85\ °C \qquad (2)$$

For frequency range 1.5 - 3.7 GHz, applying Linear approximation

$$\Delta \text{ IL, dB} = 0.107 * T - 3.55 \qquad -40\ °C < T < 85\ °C \qquad (3)$$

For frequency range, 1.5 - 3.7 GHz, applying second order Polynomial approximation,

$$\Delta \text{ IL, dB} = -0.0004 * T^{2} + 0.127 * T - 3.16 \qquad -40\ °C < T < 85\ °C \qquad (4)$$

where T is in °C.

Using eq. (1) and (2) and measurement in the frequency range from 10 MHz to 1.5 GHz, an average errors are 43% and 30% respectively. The average percentage error further can be reduced by i) increasing the order of the polynomial ii) using different approximation methods iii) extract an empirical formula for two different temperature ranges, i.e., low to ambient and ambient to high temperature. The calculated average error using eq. (3) and (4) in the frequency range from 1.5 GHz to 3.7 GHz are 5.8% and 1.8%, respectively. The errors low are due to approximately linear variation of insertion loss over the temperature range.

3.3 HUMIDITY

The purpose of the test is to determine the humidity effect on materials [5], which in turn may effect electrical parameters of the RF phase shifter. Warm, humid conditions can occur year-round in tropical areas, seasonally in mid-latitude areas, and in material subjected to combinations of changes in pressure, temperature, and relative humidity.

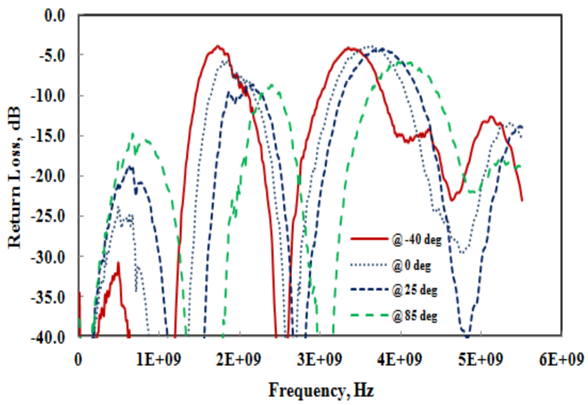
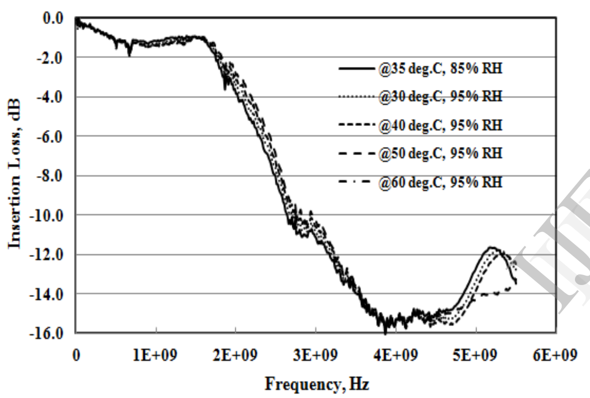
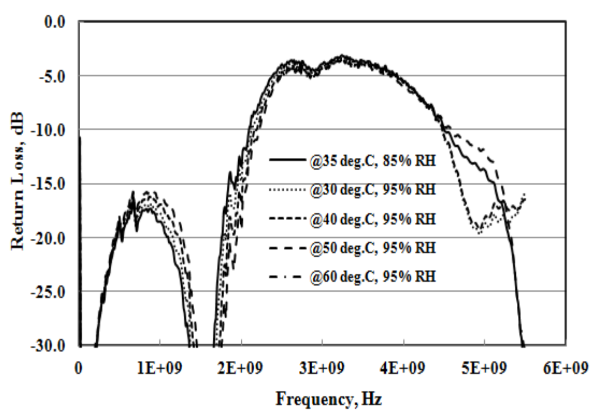


Fig. 10. Measured Return Loss of RF MEMS Phase shifter (-40 °C to +85 °C)



(a)



(b)

Fig. 11. Measured insertion loss and return loss of RF MEMS Phased Shifter at different Temperature level (@ RH, 85% and 95%)

Often material enclosed in non-operating vehicles in warm, humid areas can experience high internal temperature and humidity conditions [5]. The RF MEMS phase shifter was subjected to relative humidity of, 95%, and temperature varied from 30 °C to 60 °C in steps of 10 °C in thermal chamber. The measured insertion loss and return loss is shown in Fig. 11. The insertion loss variation was 0.5 dB up to 1.5 GHz and reduced by 2 dB between 1.5 GHz and 4.0 GHz, when the temperature was increased from 30 °C to 60 °C at 95% RH is shown in Fig. 11(a). The resonance frequency shift was observed due to temperature variation at constant RH is shown in Fig. 11(b).

3.4 PHASE

DC actuation voltage was applied between the device bit pad and ground of RF MEMS phase shifter. Maximum 2° and 10° phase shift was observed at actuation voltage of 19.7 V. Other bits were not giving phase shift even at higher voltages i.e., between 20 V and 56.0 V. In this case, the applied voltage may not be sufficient to pull the beams down state or high voltage may be required to pull down the beams. A detailed further experimental study is needed on samples.

4. FURTHER WORK

The further work on the RF MEMS phase shifter includes the packaging of RF MEMS phase shifter using Alumina substrate and measure electrical performance at different environmental conditions, such as Temperature, humidity, thermal shock, altitude (low pressure), vibration, Electrostatic discharge (ESD). Extract an empirical formula based on the experimental results, establish the standard for different environmental conditions and estimate the life time of the RF MEMS phase shifter.

5. CONCLUSIONS

In this paper, we have reported measured insertion loss and return loss results of 5-bit RF MEMS phase shifter subjected to temperature range from -40 °C to 85 °C without DC actuation voltage. As the temperature was varied from ambient to high, and ambient to low, the insertion loss maximum variation was 4.0 dB and -8.0 dB respectively, in the frequency range up to 3.7 GHz. It was observed from return loss measurement, the resonance frequency changes more than 300 MHz from low to high temperature. The total insertion loss variation, 1.5 dB, was observed in 10 MHz - 5.0 GHz, at 95% RH, from 30 °C to 60 °C temperature. The extracted empirical formulas give an estimation of the insertion loss variation over the temperature range especially when RF MEMS phase shifter is used in harsh environment.

APPENDIX

Thru Transmission Line:

The 50 ohm Transmission line, CPW configuration was designed [3] and fabricated to check whether the CPW line on the carrier PCB will provide proper impedance match on both ends before die attach and wire bonding of RF MEMS die.

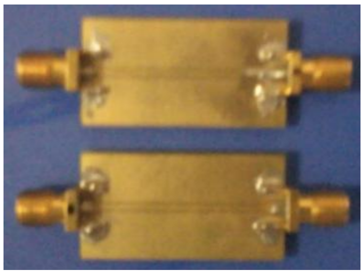


Fig. 12. Fabricated CPW Thru Transmission line

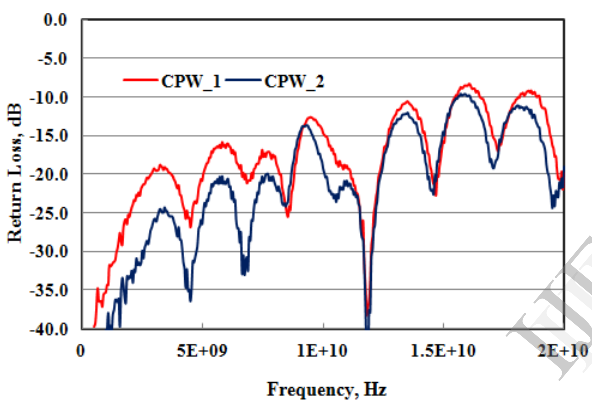


Fig. 13. Measured Return Loss of CPW Transmission line

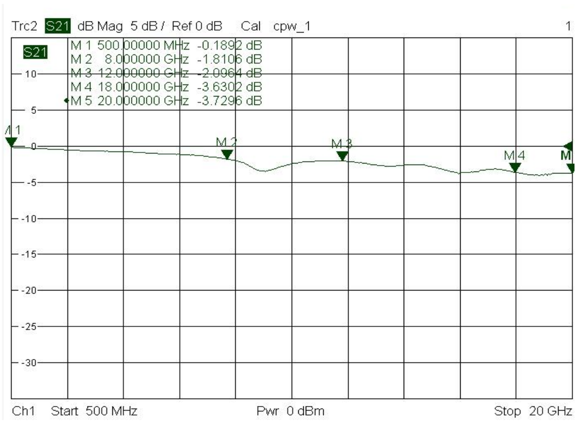


Fig. 14. Measured Insertion Loss of CPW Transmission line (Sample : CPW_1)

The design parameters of the CPW transmission line are, width, 80 mil, spacing between signal and ground, 8.1 mil, length of the total transmission line, 1320 mil, thickness of the substrate, 64 mil, and FR4 material, ε_r = 4.5 was used. Gold plating material was used on the carrier PCB. The two samples were using the CPW configuration is shown in Fig. 12. Fig. 13. Measured Return Loss of CPW Transmission line. The measured return loss of CPW transmission line of two samples are shown in Fig. 13. The return loss is better than 10 dB up to 20 GHz frequency range. The insertion loss for both samples are better than 2.0 dB up to 12 GHz frequency range. The frequency range between 12 GHz and 18 GHz, insertion loss for CPW_1 and CPW_2 are better than 4.0 dB, is shown in Fig. 14 and Fig. 15.

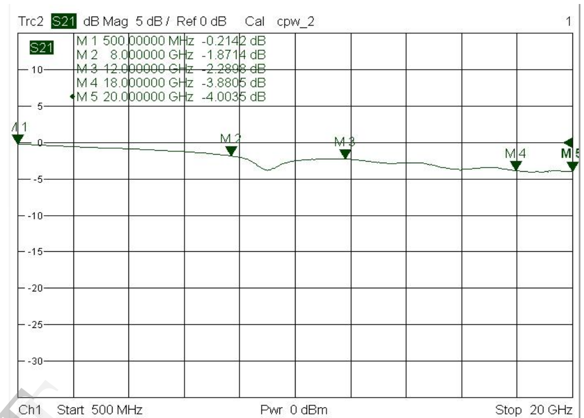


Fig. 15. Measured Insertion Loss of CPW Transmission line (Sample : CPW_2)

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