EXPERIMENTAL STUDY OF A ALUMINA PACKAGED 5-BIT RF MEMS PHASE SHIFTER IN HIGH TEMPERATURE CONDITIONS

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ABSTRACT

RF MEMS 5-bit Electrostatically actuated phase shifter die is packaged on Alumina substrate carrier. The RF MEMS phase shifter is subjected to high temperature environment from ambient (+25 °C) to +180 °C. The measured S-parameter data are evaluated in the frequency range from 0.1 to 18 GHz and compared at different temperature levels. The normalized maximum and minimum insertion loss variation observed were -5.24 dB to +0.68 dB and -13.63 dB to +13.36 dB, in the frequency range of 0.1 to 10 GHz and 10 to 18 GHz respectively, for temperature up to +180 °C. The comparison results between FR4 and Alumina package of RF MEMS phase shifter are also presented.

Keywords: Alumina, CPW Line, FR4, High Temperature, RF MEMS Phase Shifter, S-Parameters.

1. INTRODUCTION

Reliability of Radio Frequency Microelectromechanical Systems (RF MEMS) phase shifter is a critical issue and its performance at high temperature is one of the important parameters for estimation of life time. 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, defence, satellite and telecommunications systems [9]. 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 research publications are available on innovative designs through simulations on improving the electrical characteristics over the frequency band of RF MEMS phase shifters. RF MEMS phase shifter used in severe environment applications typically use low power devices that do not generate much heat to be dissipated to the environment.

A 5-bit RF MEMS phase shifter was packaged on FR4 substrate and experimental results were reported in [5], for temperature from +25 °C to +85 °C and frequency, 10 MHz - 5.5 GHz. The normalized maximum insertion loss variation was observed to be +3.7 dB in frequency range, 10 MHz - 5.5 GHz. in the temperature range from +25 °C to +85 °C. It was observed, that in the temperature range between 65 °C and +85 °C, the insertion loss variation was constant. Reliability in MEMS packaging is explained in [1] and various failure mechanisms associated with the reliability of MEMS are also presented in [1, 2]. At elevated temperature, MEMS may fail due to creep that usually occurs in components made of polymers or plastics with low homologous melting points [1]. A major reliability problem associated with MEMS devices is the degradation of material and release of gases after being sealed in packages [1] which in turn may affect electrical characteristics of RF MEMS device. The reliability of RF MEMS switch was investigated through modeling and on-chip experiments and the results were reported in [9] in the temperature range from -60 °C to 100 °C.

The objective of this work is, a) to design and fabricate a package using Alumina substrate b) measure insertion loss and return loss during high temperature environment and compare results.

The paper is organized as follows: The design and fabrication of packaging of 5-bit RF MEMS Phase shifter using Alumina substrate is explained in Section 2. High temperature environment and its specifications are briefly discussed in section 3. Experimental results and discussions are described in Section 4 and conclusions in Section 5.

2. PACKAGING OF 5-BIT RF MEMS PHASE SHIFTER

A 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 RF MEMS phase shifter die are 13.5 mm and 3.5 mm respectively. RF MEMS phase shifter was designed using Quartz \( \varepsilon_r = 3.8, \tan(\delta) = 0.001 \) material. RF MEMS phase shifter is constructed using CPW transmission line periodically loaded with shunt MEMS bridges. The design details are explained in [3]. RF MEMS phase shifter device is available in the form of wafer. The packaging process consists of wafer, placement of protective glass on selected dice with liquid glue, dicing using Co2 Laser dicing machine, design of CPW transmission line using Alumina substrate, die attach to Alumina substrate, fixing RF connectors both end of carrier PCB, interconnect between RF MEMS die and CPW line using wire bonding.

2.2 CPW Transmission line

The CPW line carrier PCB, \( Z_0 = 50 \) ohm, was designed [5] using Alumina substrate for packaging of RF MEMS phase shifter as shown in Fig. 1. The design of CPW transmission line are, \( w_1 = 80 \) mil, spacing between signal and ground, \( s_1 = 20.1 \) mil, length of line, \( l_1 = 150 \) mil. CPW line is tapered from 80 mil to 40 mil with length, \( l_2 = 75 \) mil. CPW line width, \( w_2 = 40 \) mil, \( s_2 = 14.3 \) mil, length, \( l_3 = 150 \) mil, thickness of Alumina substrate, \( t = 25 \) mil, and dielectric constant of Alumina,
\( \varepsilon_r = 9.5 \), was used. The CPW line dimensions are symmetrical on both sides. Gold plating was used on Alumina substrate PCB. The dimension of Alumina substrate carrier PCB was 1350 x 680 mil.

![Diagram showing CPW transmission line on Alumina substrate](image)

**Figure 1:** CPW transmission line on Alumina substrate
(a) Top view and (b) Top view with dimensions

2.3 RF MEMS die attach

Die attach is another important factor for packaging of RF MEMS phase shifter. The main function of the die attach is to provide mechanical support and good thermal conductivity to RF MEMS phase shifter during its exposure to vibration, shock, temperature, humidity and other environmental conditions. EPO-TEK 353ND epoxy was used to attach RF MEMS phase shifter die on Alumina carrier and kept in the oven at 100 °C for 10 minutes duration. Sub Miniature Version A, R125423200W, connectors were connected at both ends of Alumina carrier PCB between the signal line and ground. RF MEMS phase shifter die attached on Alumina substrate is shown in Figure 2.

2.4 Wire bonding

The CPW transmission signal and ground line are connected to the corresponding signal and ground of RF MEMS die using wire bonding. Aluminum wire was used for wire bonding in an ultrasonic bonding process using HB16, wire bonder. The actuation pads on RF MEMS die are connected to the corresponding pads on the carrier PCB using wire bonding. The wire diameter used is 33µm. Each bit of phase shifter and ground of CPW transmission line can be used for DC actuation. A packaged 5-bit RF MEMS phase shifter using Alumina substrate is shown in Figure 2.
3. HIGH TEMPERATURE ENVIRONMENT

The use of RF MEMS switches, in applications such as aircraft condition monitoring and distributed satellite communication, present a unique challenge for device design and reliability [8]. The real application of RF MEMS requires working without any performance degradation or within the tolerance of the mechanical or electrical performance in the natural or severe environment conditions. High temperature is one of the parameters as per MIL STD 810G [6] and is to evaluate material or devices likely to be deployed in areas where temperatures are higher than standard ambient. The data is to help to evaluate the effects of high temperature conditions on material safety, integrity, and performance of the device [6]. High temperatures may temporarily or permanently impair performance of material or device by changing physical properties or dimensions of the material of which it is composed. Some of the problems that could result from high temperature environment are parts material change in dimension, differential expansion of dissimilar materials, overheat of components etc. in [6].

There are two types of climatic categories where high temperature is encountered, basic hot and hot dry. In basic hot and hot dry category regions, the temperature can be from 30 °C to 60 °C and 33 °C to 71 °C respectively. Material exposed to solar radiation conditions, the temperatures can be as high as 71 °C to 85 °C [6]. Applicable conditions for such testing include equipment that is employed in the open and in enclosed compartments having glazed or transparent panels (aircraft cockpits, vehicle compartments, etc.). Man-made heat-producing devices such as motors, engines, power supplies and high-density electronic packages etc., may significantly raise the local air temperature near the material, either by radiation, convection, or impingement of exhaust air.

In special conditions, although high temperature testing is generally based on the average temperature of the air envelope surrounding the material, significant localized heating can occur because of special heating conditions. This localized heating can be well above the average surrounding air and therefore can significantly affect the evaluation of the material thermal behaviour and its performance. Thermal cycling, max. cold and hot temperature, from -65 °C to +300 °C for E type of test conditions for microelectronic devices suitable for military and aerospace electronics system is mentioned in [7]. For F type of test conditions, cold and hot temperature are from -65 °C to +175 °C.

The highest temperature for some selected Test conditions are given in Table 1. Considering all the combinations of high temperature conditions and material deployment, we decided to study experimentally, the withstanding capability of RF MEMS phase shifter subjected to the highest temperature environment up to 180 °C.
Table 1: Specifications of High Temperature for different MIL Standard

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>High Temperature, ºC</th>
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<tbody>
<tr>
<td></td>
<td>MIL STD 810G [6]</td>
</tr>
<tr>
<td></td>
<td>MIL STD 883J [7]</td>
</tr>
<tr>
<td></td>
<td>MIL STD 202G [8]</td>
</tr>
<tr>
<td>High temperature</td>
<td>85 (Solar radiation)</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>-</td>
</tr>
<tr>
<td>Thermal cycling</td>
<td>-</td>
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4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The package level measurement was carried out using ZVA24 Vector Network Analyzer. The measured insertion loss and return loss of RF MEMS phase shifter at ambient (+25 ºC) are shown in Fig. 3. Actuation voltage was applied to bit between 10 V and 50 V to measure the phase shift of the device. There was no phase shift found because of the cantilever beams were not responding to the given voltage due to residual stress. The measurements were carried out without DC actuation voltage to bit. The insertion loss was better than -10 dB up to 11 GHz and decreased beyond 11 GHz. The return loss was better than -5 dB, up to frequency 5.0 GHz. The poor performance is due to the wire bond length, and mismatch between the RF MEMS phase shifter die and wire bond length, and also between wire bond length and carrier PCB, PCB trace and connector solder junctions. The better performance can be achieved by further reducing wire bond length.

![Fig. 3: Insertion loss and Return loss of RF MEMS Phase shifter at +25 ºC without actuation voltage to bit](image)

Temperature chamber was used to carry out the measurements, from ambient to +180 ºC. The measured insertion loss and return loss were recorded as the temperature increased from ambient to +180 ºC. The measured insertion loss from 40 ºC to +180 ºC was normalized w.r.to ambient and is shown in Fig. 4 and Fig. 5.
The normalized insertion loss is defined as:

As an Example at 40 ºC, Normalized insertion loss (Δ IL), dB = (Measured Insertion Loss, dB, at +40 ºC) - (Measured Insertion Loss, dB, at ambient (+25 ºC)).

**Fig. 4:** Normalized measured insertion loss of RF MEMS Phase Shifter (+40 ºC and +80 ºC)

[Graph showing normalized insertion loss vs frequency for 40 ºC and 80 ºC]

**Fig. 5:** Normalized measured insertion loss of RF MEMS Phase Shifter (+100 ºC and +180 ºC)

[Graph showing normalized insertion loss vs frequency for 100 ºC and 180 ºC]

As the temperature increased, the insertion loss decreased to -5 dB around 6 GHz. At around 11.2 GHz, at higher temperatures, the insertion loss increased and started to decrease to 0 dB and again decreased to -10 dB at 12.2 GHz. The cyclic variation was observed from 11.0 to 12.5 GHz frequency range. At +180 ºC temperature, the maximum insertion loss variation was observed at 11.3 GHz, 12.5 GHz, and 13.4 GHz, whereas the minimum insertion loss variation was at 12.6 GHz.
frequency. The total insertion loss variation in two different frequency bands at different temperature level are shown in Table 2

**Table 2:** Maximum and Minimum Insertion Loss variation over frequency band from 0.1 to 18 GHz w.r.to +25 °C

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>0.1-10 GHz</th>
<th>10 - 18 GHz</th>
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<tbody>
<tr>
<td></td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0.09</td>
<td>-0.19</td>
</tr>
<tr>
<td>60</td>
<td>0.35</td>
<td>-1.59</td>
</tr>
<tr>
<td>80</td>
<td>0.29</td>
<td>-1.90</td>
</tr>
<tr>
<td>100</td>
<td>0.48</td>
<td>-4.03</td>
</tr>
<tr>
<td>160</td>
<td>0.60</td>
<td>-4.70</td>
</tr>
<tr>
<td>180</td>
<td>0.68</td>
<td>-5.24</td>
</tr>
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</table>

To estimate power ratio insertion loss variation for any given intermediate temperature in Table 2, the following procedure can be used.

Insertion loss, (IL) dB = 10 x log(P_o/P_i)         \hspace{1cm} (1)

Power ratio or P_o/P_i = 10^{(\Delta IL, dB/10)} \hspace{1cm} (2)

where \( P_i \) and \( P_o \) are input and output power of device respectively. We converted \( \Delta IL, dB \), into power ratio using relation (2). From 0.1 to 10 GHz frequency band and temperature range from 40 °C to 180 °C, the \( \Delta IL \) maximum and minimum are +0.68 dB and -5.24 dB respectively, whereas in 10 to 18 GHz frequency band, \( \Delta IL \) maximum and minimum insertion loss are -13.63 dB and -13.36 dB respectively. The normalized measured maximum and minimum power ratio variation over the temperature range in two frequency bands are shown in Fig. 6 and Fig. 7 respectively.

![Normalized measured power ratio insertion loss power ration variation (0.1 - 10 GHz) of RF MEMS Phase Shifter](image)

**Fig. 6:** Normalized measured power ratio insertion loss power ration variation (0.1 - 10 GHz) of RF MEMS Phase Shifter
From Fig. 6 and Fig. 7, it can be observed that, in both frequency bands, the maximum insertion loss variation increases as the temperature increases and also minimum insertion loss variation decreases as temperature increases.

This is due to co-efficient of thermal expansion (CTE) of materials used in package and also in RF MEMS phase shifter. The dimensional changes can occur because of CTE of materials used on the package and RF MEMS phase shifter die. Because of the dimensional change due to high temperature, in turn changes the basic electrical parameters, inductance (L), and capacitance (C) of the total package of RF MEMS phase shifter. These changes can also lead to change in impedance characteristics of overall package, i.e variation in return loss and insertion loss parameters.

Considering frequency from 10 to 18 GHz, the contributing factors for high variation of insertion loss due to high temperature are i) dielectric constant variation of Alumina ii) linear coefficient of thermal expansion of Alumina substrate iii) relative physical dimension variations of RF MEMS phase shifter and Alumina substrate iv) capacitance and inductance variations over the frequency band and v) inductance of the wire bond length.

The comparison of insertion loss variation of a packaged 5-Bit RF MEMS Phase shifter using FR4 and Alumina substrate is shown in Table 3. Comparing, FR4 [4] and Alumina substrate packages, Alumina package provides better insertion loss variation up to 5.5 GHz and temperature up to 80 °C.

Table 3: Comparison of insertion loss variation of a using FR4 and Alumina packaged 5-Bit RF MEMS Phase shifter w.r.to +25 °C

<table>
<thead>
<tr>
<th>Frequency range, GHz</th>
<th>Temperature range, °C</th>
<th>Δ IL, dB ( Min, Max )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 - 5.5</td>
<td>25 - 80</td>
<td>FR4 [4]</td>
</tr>
</tbody>
</table>
Insertion loss variation over high temperature can be considered as one of the important parameters when packaged RF MEMS phase shifter is operating in severe high temperature environmental conditions.

5. CONCLUSIONS

In this paper, we compared the variation of insertion loss from ambient to high temperature of a packaged 5-bit RF MEMS Phase shifter using Alumina substrate. The insertion loss variation of Alumina package RF MEMS phase shifter was between +0.29 dB and -1.90 dB up to 10 GHz, for temperature up to 80 ºC. Though RF MEMS phase shifter was working up to +180 ºC, the performance of insertion loss variation was high between 10 and 18 GHz frequency range. Measurement results clearly indicate that the performance of a packaged RF MEMS phase shifter is temperature dependent.

REFERENCES