Investigation of material properties for polymer-based microwave devices

Iurii Cherukhin¹, Felix V Zander², Alena K Dashkova² and Yong Xin Guo¹

¹ Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, 117583, Singapore
² Department of Radio-Electronic Systems Engineering, Institute of Physics and Electronics, Siberian Federal University, Kiresky st., 28, 660074, Krasnoyarsk, Russia

E-mail: FZander@sfu-kras.ru, ADashkova@mail.ru, yongxin.guo@nus.edu.sg

Abstract. This work demonstrates that the molding technique for polymer-based flexible microwave electronics with various polymers in order to evaluate acceptable boundaries for conductivity and tan loss. Performance evaluation has been done on the microstrip line and patch antennas with and without material improvements. We have demonstrated that improvements in conductivity after $10^6$ S/m do not give significant benefits. The attenuation in microstrip lines has been reduced from 0.16 dB/cm to 0.05 dB/cm. However, reduction in the tan loss is able to boost antenna gain from 4.2 dBi to 6.5 dBi.

1. Introduction
Significant developments in flexible electronics demonstrated that there are still many challenges, especially when it comes to microwave devices, due to the strict requirements of fabrication tolerances, material properties, and reliability. An ambiguous trade-off between electrical and mechanical properties of materials makes flexible and stretchable microwave components very difficult in realization, i.e., low loss dielectrics are stiff and highly conductive materials are not able to stretch more than 1%. The possible realization has been investigated previously where conductive layers can be made using conductive fabrics [1], sputtered, printed and electroplated metals on polyimide [2], [3], [4], [5]. Unfortunately, these methods suffer from many disadvantages; lack or even absent of stretchability for conductive fabric and polyimide, a metallization layer is way thinner than 1um in the case of sputtering. It is inevitable to use elastomers as dielectrics materials, and most common are 3D printed flexible polymers, PDMS (polydimethylsiloxane), and latex rubber. However, the most promising solution is to use a fully polymer-based method, where conductive and dielectric materials are elastomers. This approach was investigated in [6], [7], [8].

We have demonstrated in our work [9] that molding production method gives very good precision, reproducibility, low surface roughness, and controlled thickness compare to screen-printing or a “brushing” techniques. Since we are able to engineer materials, it is necessary to determine the acceptable boundaries and trade-offs for material properties. We have compared the performance of microwave devices, such as a microstrip line and patch antenna made from commercially available polymers and from improved materials.
2. Design

2.1. Materials

Among all types of elastic polymers, PDMS was chosen as a base dielectric material, due to its versatility in production, biocompatibility, extremely low reactivity with various solvents [10], and capability to tune mechanical properties. Dielectric properties of Dow corning Sylgard 170 were measured using a transmission line technique. Although Sylgard 170 has a carbon black filling it is similar to its mechanical and dielectric properties to Sylgard 184. Although, the dielectric constant of Sylgard 170 is 3.1 while Sylgard 184 has 2.8.

![Figure 1](image.png)

Figure 1. Measured dielectric constant and dielectric loss of Sylgard 170 and modified PDMS.

Another type of PDMS was modified in order to reduce dielectric loss. Figure 1 shows that tan loss became 0.003 at 2.6GHz, and it is comparable to commercially available PCB substrates like RO4003C or RO4350B, which have tan loss 0.0027 and 0.0037 accordingly. Modified PDMS is very elastic. A proper review on modified dielectric and conducting material will be done in a separate publication.

The conducting layers were made using conducting polymers from EMS company. All polymers have 60% silver nanoparticle filling in an “uncured” state. We purchased 3 types of polymers (table 1). Conductivity measurements were done by the 4-point probe technique. It turns out that that conducting polymers are having slightly different conductivity, viscosity, surface roughness, stretching and bending abilities than it stated in datasheets.

|                | CI-1036 | CI-1036 modified | CI-1075 | CI-4040 |
|----------------|---------|------------------|---------|---------|
| Datasheet       | 3.9*10^6| 3.6*10^6         | 0.78*10^6|
| Conductivity    | 1.6*10^6| 6.75*10^6        | 4.2*10^6| 0.7*10^6|

The variations in the stated and measured conductivity might be due to inappropriate transportation, storage, or contamination. CI-4040 is the most stretchable polymer, while CI-1075 is very brittle. The most promising polymer is CI-1036, we have managed to tune stretchability and conductivity, which
gives engineering freedom in order to obtain the optimum mechanical/electrical performance for flexible polymer-based microwave devices. Apart from material engineering, we have developed a mold releasing technique and several recipes for chemical adhesion between PDMS and conducting polymers.

2.2. Design of patch antenna and microstrip line

The patch antenna has been chosen as a resonance type of antenna in order to evaluate the effects of dielectric loss and conductivity on its performance. The design guide is provided by [11], where the microstrip is used as a feeding network (figure 2). The same microstrip is used to evaluate propagation loss for quasi-TEM wave configuration.

![Figure 2. Photo of the patch antenna and microstrip.](image)

It is inevitable to have two different configurations due to differences in dielectric constants of Sylgard 170 and modified PDMS. The microstrips width (W) is 8.1 and 11.5mm, 44.6 and 51.5mm patch width (Wp), 32.2 and 41.2mm patch length (Lp), 1.3 and 2.4mm insertion gap, 11.5 and 12.8mm insertion length, and feeding length (Lf) is 40mm for both cases. The molding approach provides excellent reproducibility in terms of dimensions from batch to batch. Several types of designs have been done and shown in table 2. All antennas have been designed to have central frequency at 2.5GHz.

| Description                  |          |
|------------------------------|----------|
| Design 1                     | Sylgard 170 and CI-1036 |
| Design 2                     | Sylgard 170 and improved CI-1036 |
| Design 3                     | Sylgard 170 and CI-1075 |
| Design 4                     | Sylgard 170 and CI-4040 |
| Design 5                     | Modified PDMS with Dk 1.85 and tan loss 0.003 and CI-4040 |
| Design 6                     | Modified PDMS with Dk 1.85 and tan loss 0.003 and improved CI-1036 |

The first four and the last two designs are having the same physical dimensions. The substrate thickness is 3mm and “metallization” thickness for ground and signal plane is 150um (five skin depths or more) for all cases.
3. Performance comparison

3.1. Microstrip

S-parameters have been measured using PNA N5227A after attachment of 2.92mm end launch connectors to 12cm long microstrip lines. Unfortunately, the microstrip line from design 6 has too many defects and has been excluded from analysis. Figure 3 and 4 show discrepancy of S$_{21}$ parameters for frequencies higher than 3GHz. Having thick substrate (3mm) not only results in increase of the radiation loss, but also limits operational frequency up to 7GHz. The higher propagation modes start appearing when the substrate thickness becomes comparable to 10% or more of the wavelength. Additionally, to these factors we have to consider the impedance mismatch, insertion loss, nonlinear tan loss and possible imperfections in production, e.g. air traps or surface roughness.

![Figure 3](image1.png) **Figure 3.** Measured and simulated S-parameters of the microstrip line on Sylgard 170.

![Figure 4](image2.png) **Figure 4.** Measured and simulated S-parameters of the microstrip line on modified PDMS.

![Figure 5](image3.png) **Figure 5.** Measured attenuation in microstrip lines on Sylgard 170.

![Figure 6](image4.png) **Figure 6.** Measured attenuation in microstrip line on modified PDMS.

To exclude insertion loss and mismatch we have de-embedded and extracted attenuation per centimeter (figure 5 and 6). Analytical solution for ohmic and dielectric loss at 2.5GHz, in quasi-TEM wave configuration, has been done based on [12]. The analytical results for ohmic losses can be overestimated in the case of the quasi-TEM wave. Additionally, we have compared to full EM simulation in CST studio suite. Table 3 shows a comparison among analytical, full EM wave simulation,
and measured results. The first 3 designs have materials conductivity more than $10^6 \text{ S/m}$ and show little differences in attenuation loss. However, reduction below $10^6 \text{ S/m}$ has a drastic effect on the microstrip performance, which means it is possible to tune the polymer flexibility on account of conductivity in order to obtain superior flexibility of the devices. On the other hand decrease in the dielectric loss has proportional effect on the attenuation. It seems that further reduction is necessary to achieve reasonable performance on even higher frequencies.

Table 3. Theoretical and measured loss in microstrip line at 2.5GHz.

| Design | Analytical solution (dB/cm) | CST simulation (dB/cm) | Measured (dB/cm) |
|--------|-----------------------------|------------------------|------------------|
|        | Loss in dielectric | Ohmic loss | Cumulative | Cumulative |
| 1      | 0.072                   | 0.055               | 0.062          | 0.085      |
| 2      | 0.072                   | 0.032               | 0.058          | 0.078      |
| 3      | 0.072                   | 0.042               | 0.059          | 0.092      |
| 4      | 0.072                   | 0.095               | 0.067          | 0.166      |
| 5      | 0.011                   | 0.095               | 0.028          | 0.05       |
| 6      | 0.011                   | 0.032               | 0.02           | ---        |

3.2. Patch antenna

S-parameters for antennas have been measured and shown in figure 7 and 8. All antennas have good correspondence to simulation results. Slight shifts of the central frequency are due to mechanical bending during measurements.

The antennas gain has been measured in an anechoic chamber and shown in figure 9 and 10. Measurement results are showing the maximum gain at a particular frequency within the main lobe. This has been done to exclude the effects of occasional bent antennas and design imperfections. The feeding network has a slight influence on the radiation pattern. It is tilted by about 5 degrees towards the feeding network.

Figure 9 and 10 show that one order changes in “metallization” conductivity give only 0.4dBi boost to the antenna gain. However, reduction of the dielectric loss about 4 times gives additional 1.6dBi. S-parameters and the antenna gain show that the antennas bandwidth vary, and it is usually directly related to the dielectric constant and loss tangent.
to the quality factor, but we might be cautious when it comes to flexible implementation since slight physical deformations significantly effect on antenna’s performance.

Figure 9. Realized antennas gain (Sylgard 170).

Figure 10. Realized antennas gain.

4. Conclusion

We have demonstrated that the molding techniques and material engineering can boost the performance of flexible microwave devices. Improvements in the materials conductivity for more than $10^6$ S/m do not give significant effects and can be set as a lower boundary for flexible microwave devices operational at S-band frequencies. On the other hand, the dielectric loss decrease has proportional effects on the loss and antenna gain and must be engineered carefully in order to get optimum performance.

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