Three dimensional metal micromachining: A disruptive technology for millimeter-wave filters

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Abstract — The development of silicon based integrated circuits has reached a point where a large portion of an RF system can be integrated onto a single die. However, to create complete RF/millimeter-wave systems, it is necessary to integrate this silicon die with several high performance passive components. Specifically, silicon integrated circuits tend to have limited performance for the design of transmission lines, filters, and antennas. The Polystrata process is a three dimensional metal micromachining process that addresses these weaknesses by providing monolithic fabrication of high performance passives. When applied to filters and upper microwave and millimeter-wave frequencies, metal micromachining can provide filter performance comparable with that of waveguide technology but 10-100x smaller. In this presentation, we will provide details of the Polystrata process, and show the performance that can be achieved with filters fabricated using this technology.

Index Terms — Ceramics, coaxial resonators, delay filters, delay-lines, power amplifiers.

I. INTRODUCTION

Silicon based technologies including RF silicon, BiCMOS, and SiGe are playing an increasing role in the design of RF, microwave and millimeterwave (mmWave) systems. The primary driver for this is the cost advantage that silicon can provide. However, a secondary benefit is the increased level of integration which often provides performance advantages in addition to the cost advantages.

Despite the success of silicon in integrating most to all of the active devices in mmWave transceivers, the relatively high loss of passives on silicon means that filters implemented on silicon have unacceptably high loss for most communication systems. At the same time, antennas on silicon typically have poor efficiency and are often not compatible with standard silicon packaging.

The PolyStrata® process was developed under the DARPA 3D MERFS program to directly address the performance limitations of planar thin film technologies on substrates like Si and GaAs. This process is a thick film metal micromachining process with integrated dielectrics. It enables the fabrication of rectangular coaxial transmission lines that offer a combination of:

- Wide-bandwidth: DC to over 250 GHz [1,2];
- Low loss: Measured losses below 0.1dB/cm at K_a-band [1];
- High line-line isolation: Isolation between two 1 cm lines sharing a common wall has been measured to be greater than 70 dB [3].

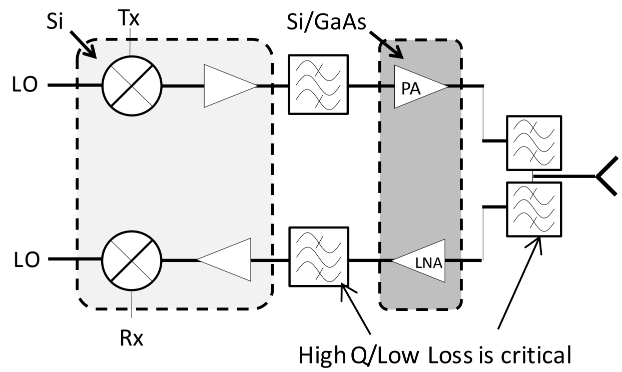

Figure 1. Simplified schematic of a mmWave transceiver front end. Silicon circuits are increasingly being used for the down conversion and amplification other than the PA and LNA. Currently, the PA and LNA are primarily GaAs or InP based, but silicon technologies are playing an increasing role here for cost sensitive applications. Despite the success of silicon in replacing active components, silicon technology has had very limited success in replacing the front end filters and the antennas.

The ability of the PolyStrata to realize relatively thick (≈ 1 mm) metal structures makes it well suited to implementing both low loss filters and high performance antennas. Utilizing PolyStrata technology, low loss filters have been implemented at frequencies from 5 GHz up to 90 GHz. These filters have shown performance comparable to much larger comb-line or waveguide filters while offering size reductions of 10-100x. PolyStrata has also been used to implement high performance antennas at mmWave frequencies including a patch antenna with 95% radiation efficiency at K_a-band [4]. The following sections provide examples of a high performance mmWave tunable filter at K_a-band, an E-Band diplexer, and K_a-band mmWave antennas.

II. TRANSMISSION LINES

The PolyStrata process is a sequential micromachining process which is used to fabricate 3-D structures [6] using electroplated copper and periodic dielectric supports. In traditional microwave transmission lines, material losses become more significant at mm-wave; however, Polystrata structures have air dielectrics, significantly mitigating this issue. Micro-coaxial lines have much higher isolation when compared with other microwave transmission line technologies, allowing for increased routing density. Additionally, lines can be routed in three dimensions for crossovers. Figure 2 provides a rendering of a coaxial line transitioning from one layer to the next, while Figure 3 provides the measured loss for a 1-cm line.

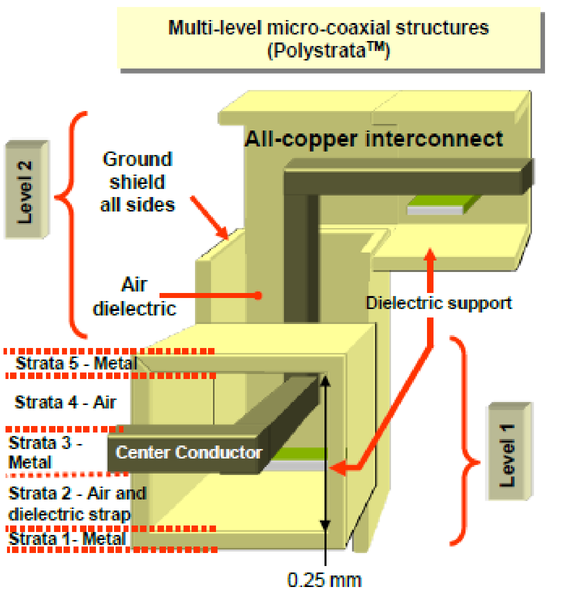

Figure 2. Using PolyStrata, rectangular coaxial lines with dielectric supported center conductors can be fabricated. Multiple layers of coaxial lines can be monolithically fabricated enabling complex signal routing with low loss and extremely low signal cross talk.

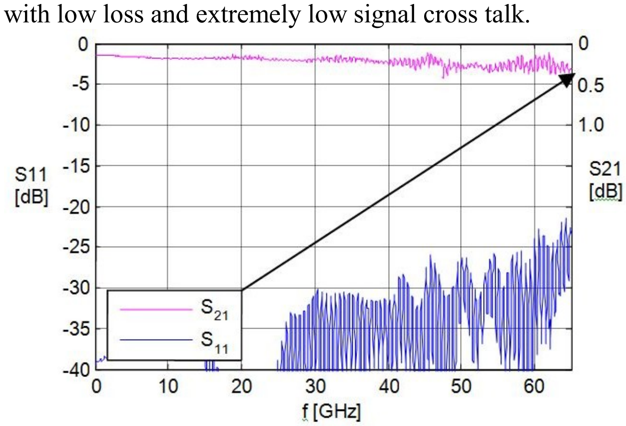

Figure 3. Measured loss for a 1 cm long rectangular coaxial line fabricated using the PolyStrata process.

II. FILTERS

The loss of a band pass filter can be calculated as:

$$\Delta L_a \approx 8.686 \frac{C_n}{w} \frac{1}{Q_u} \qquad (1)$$

where ΔL_a is loss in the filter, C_n is a constant related to the particular filter design, w is the fractional bandwidth of the filter, and Q_u is the unloaded quality factor of the resonators used to fabricate the filter. In evaluating this equation, it becomes apparent that the unloaded resonator quality factor (Q_u) is the only term related to the specific technology that is used to implement the filter. It is also apparent that for comparing filter technologies, it is better to evaluate resonator quality factor and not the reported insertion loss of a filter. PolyStrata filters have been implemented at frequencies from K_u-band up to W-band with quality factors in excess of 1,000. This is 5-20x higher than resonator quality factors achieved using microstirp lines on Si or GaAs.

In addition to the potential for low loss, PolyStrata also provides an environment that is enclosed by metal on all sides. This provides major advantages by eliminating unwanted package modes that can result in spurious pass bands for non-shielded filters.

Recently, PolyStrata was used to implement a K_a-band tunable filter. This filter, shown in Figure 4 consists of a PolyStrata filter body loaded with a thermally actuated MEMS resonator. The filter is designed as a two-pole band pass filter with a 200 MHz pass band at 34 GHz (0.59%). The filter was designed using Ansoft HFSS to simulate the metal filter body. This simulation accounts for all of the input/output and resonator couplings, and includes all anticipated metal losses. Ideal loads (series connected capacitor-resistor-ground circuits) are added to the filter body simulation using a circuit simulator. The capacitance and resistance values were adjusted to get the fit shown in **Figure 5**. The filter was tuned over a frequency range of 34.2-35.7 GHz with a measured insertion loss ranging from 2.4-2.9 dB. This loss translates to an unloaded resonator quality factor in excess of 500, 10x higher than has been reported for any other tunable filter fabricated with a planar technology at this frequency range. The filter is very compact measuring 6.55 x 2.80 x 2 mm.

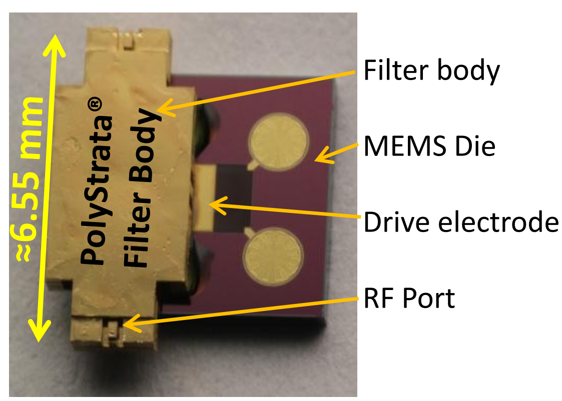

Figure 4. A PolyStrata Ka-band tunable filter. The filter body is approximately 6.55 x 2.80 x 0.8 mm, and is mounted onto a MEMS die.

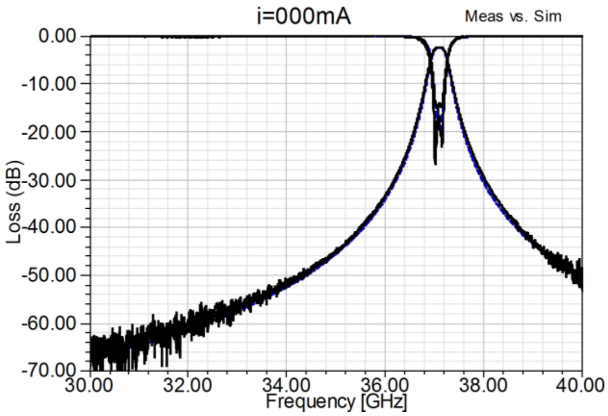

Figure 5.Measured scattering parameters of a K_a-band tunable filter compared with the simulated performance.

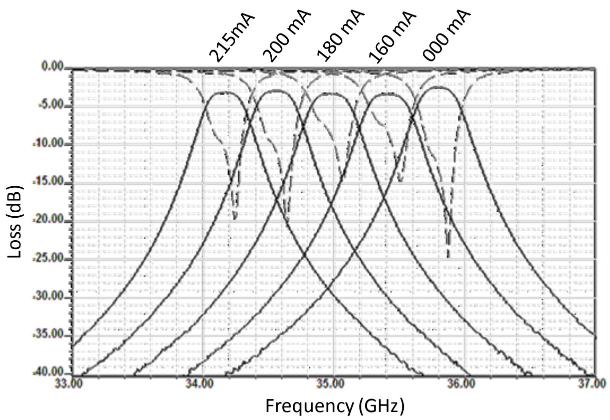

Figure 6. Scattering parameters of a K_a-band filter tuning from 34.2-35.7 GHz.

A major advantage of PolyStrata as compared to traditional fabrication techniques is the ability to integrate parts together. As a demonstration of this, we have realized an E-band diplexer. This diplexer is formed from two 6-pole filters, one with a 71-76 GHz pass band and one with a 81-86 GHz pass band. This filter, measuring approximately 4.25 x 11 x 2 mm, is shown sitting on a WR-12 waveguide flange in flange in Figure 7. As shown in Figure 8, the diplexer has a mid-band insertion loss around 1.0 dB with over 58 dB channel to channel isolation.

IV. ANTENNAS

As with the ability to integrate multiple filters together, PolyStrata can co-fabricate high-efficiency antenna elements. PolyStrata has been used to implement a range of antennas including high efficiency patch antennas at Ka- [7,8] and W-bands [9]; wideband log-periodic antennas covering X- through Q-bands [10,11]; and frequency scanned antennas at G-Band (140-220 GHz).

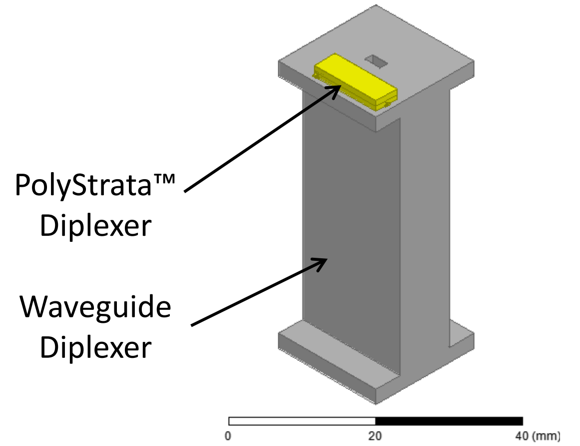

Figure 7. A PolyStrata E-Band diplexer sitting on a WR-12 waveguide flange.

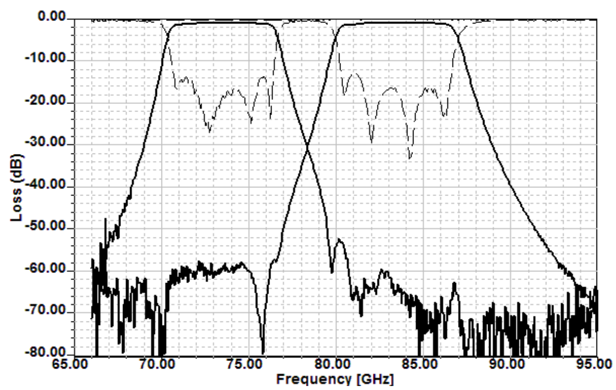

Figure 8. Measured performance of a PolyStrata E-band diplexer.

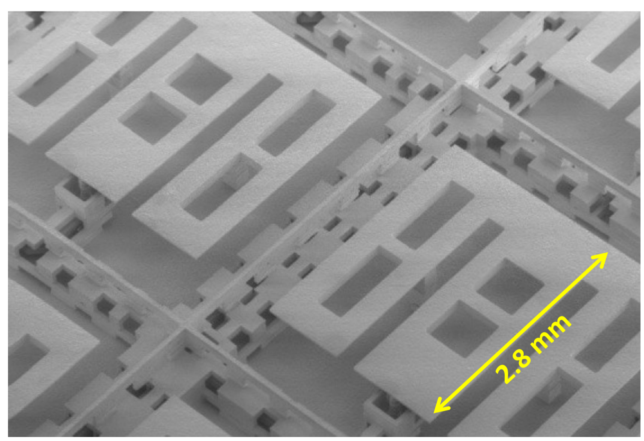

Figure 9. An image showing an E-shaped K_a-band patch antenna. The patch measures 2.8 x 3.2 mm and is suspended 0.75 mm above the ground plane. It has a simulated directivity and efficiency of 6.8 dBi and 95% respectively [7].

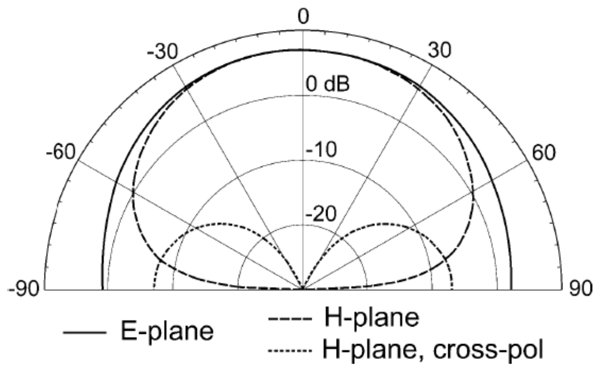

Figure 10. Simulated radiation pattern for the E-shaped patch antenna shown in Figure 9.

One example of a K_a-band PolyStrata patch antenna is shown in Figure 9. The antenna is suspended in a cavity that is 0.75 mm deep. It is designed to fit in a λ/2 pitch at 36 GHz. The patch itself measures 2.8 x 3.2 mm. Two slits are added to improve the match at the design frequency. The two slits give the antenna the shape of an E, and therefore this type of design is typically referred to as and E-shaped patch antenna. This design has also been scaled to operate at W-Band [9]. The simulated radiation pattern for this element is shown in Figure 10. The antenna has a simulated directivity and efficiency of 6.8 dBi and 95% respectively.

IV. SUMMARY

The PolyStrata process is a thick-film metal micromachining process with integrated dielectric supports. It enables the monolithic fabrication of high performance passive components a microwave and millimeterwave frequencies. This technology provides a good complement to the integration and actives that can be fabricated using silicon technologies. The result of combining PolyStrata and silicon technologies is a new level of integration that provides high performance in a very compact size.

ACKNOWLEDGEMENT

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