60 GHz Antenna on Metallic Nanowired Membrane Substrate

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Abstract— This work presents the analysis of the novel metallic nanowired membrane (MnM) substrate for designing antennas at the 60 GHz frequency band. The fabrication process of a rectangular patch antenna on the MnM-substrate is presented in detail. The antenna is fed through a modified microstrip line with slow-wave effect in order to reduce the feed line width. The fabrication is done in two phases, first the microstrip circuits are fabricated on a 50-μm-thick membrane; then it is assembled on a mechanical base to accommodate the two different substrate thicknesses used for the antenna and the slow-wave transmission line. The structure is simulated using a 3D EM software and the results indicate this substrate is a viable choice for antenna design, however gain increasing techniques must be used because of the high dielectric constant of the substrate.

1. INTRODUCTION

Given the need for gigabit data transfer rates and the fact that the microwave spectrum is already saturated with a great number of protocols and applications, the mm-wave frequency range, which comprises frequencies from 30 GHz to 300 GHz, is getting more and more attention since early 2000s. Among these, the 60 GHz frequency has been the focus of several researches for household and short-range wireless data transfer applications [1].

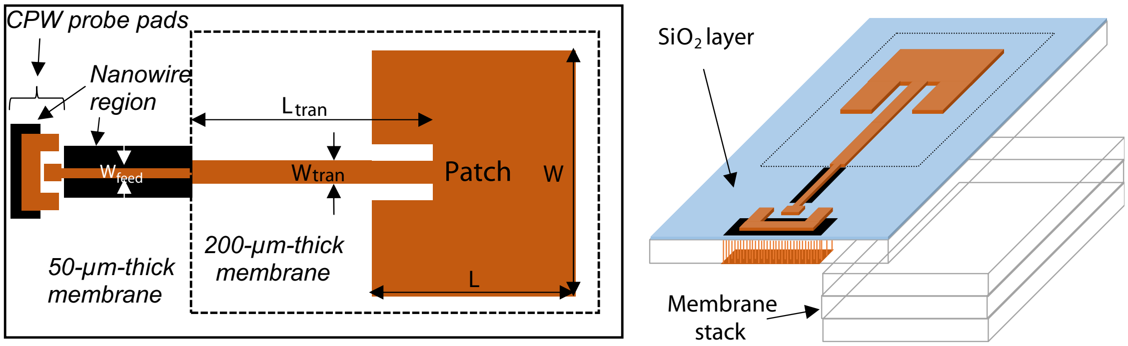
Despite of the reduction in size of lambda-based passive circuits at mm-waves, there is still an issue regarding low-cost integration, especially for antennas, which always occupy a large area. Antennas operating at mm-waves present sizes ranging from hundreds of micrometers up to a few millimeters [2], which enables the integration of planar antennas with transceivers either as a System-on-Chip-(SoC) [3] or as a System-in-Package (SiP). SiP avoids the complications of using semiconductor substrates and IC manufacturing processes, which are not entirely optimized for mm-wave passive components. Antennas manufactured using the SiP technique can employ alternative substrates, such as low temperature cofired ceramic (LTCC) [4], fused silica [5], liquid crystal polymer (LCP) [6], and Teflon [7]. They can also make use of gain increasing techniques, such as arrays and beam steering, to compensate loss caused by the abrupt signal attenuation at 60 GHz, and avoid fading issues. In order to reduce passive circuit elements even further, circuits based on slow wave concepts have been presented using different techniques and materials to reduce the phase velocity [8]. However, having the antenna fabricated in a different substrate often leads to extra interconnections using vias, which tend to be lossy, bulky, costly and hard to fabricate at mm-waves.

The metallic nanowired membrane substrate (MnM) allows an easy hybrid integration of slow-wave and classical, non-slow-wave, passive circuit elements on the same low-cost substrate [9]. This great advantage associated to a high substrate dielectric constant ($\varepsilon_r = 9.8$), motivated this work. We present the design and fabrication of a rectangular patch antenna on the MnM-substrate in order to determine whether it is a viable choice in high efficiency mm-wave antenna designs.

2. DESIGN

The MnM-substrate, as explained in [9], consists of a nanoporous alumina membrane with a thickness of 50 μm filled with copper nanowires in specific regions, a copper ground plane on its underside, and a silicon dioxide layer on its upper side. The advantage of this substrate is to allow hybrid integration of slow-wave structures with non-slow-wave structures. The MnM-substrate provides two different dielectric constants: 9.8, which is the porous alumina without nanowires, and an effective dielectric constant, ε_{reff}, of about 30 in the regions with nanowires. These nanowires yields the slow-wave effect, which increases ε_{reff} that leads to miniaturization by trapping the electric field in the thin oxide region.

Given the novel nature of this substrate and the need to investigate whether it is viable as an antenna substrate, the authors chose a rectangular patch antenna structure since it is very well



(a) (b)

Figure 1: Patch antenna structure, being (a) a top view and (b) a perspective view of the antenna structure and its substrate.

modeled and understood and widely available in technical literature. Fig. 1 illustrates the proposed antenna.

For an antenna to irradiate efficiently, the substrate should be thick and its ε_r close to 1, so the value chosen for ε_r was the smallest one, 9.8. On the other hand, there is a limit for the substrate thickness, beyond which loss due to surface waves has to be accounted for. (1) gives the maximum substrate thickness h before surface wave propagation can exist [10]:

$$h = \frac{n * c}{4 * f_r * \sqrt{\varepsilon_r - 1}} \tag{1}$$

where c is the speed of light. If the resonant frequency f_r of the proposed antenna is 60 GHz and $n = 1$ for the first excited surface wave mode TE_1, h results in $\sim 421\,\mu\mathrm{m}$. A compromise is required for the substrate thickness, since thicker substrates means more efficient antennas, but wider transmission lines will be required to connect to the antenna.At 600 GHz, the dimensions of a transmission line can become comparable to the dimensions of the antenna, degrading its performance.

The thickness of 2000 μm was chosen for this antenna. This thickness was obtained with the stacking of three 50-μm-thick membranes below the membrane on which the antenna was fabricated.

Once ε_r and h are defined, the patch width W and length L were theoretically defined to be $W = 1200\,\mu\mathrm{m}$ (2), and $L = 800\,\mu\mathrm{m}$ (3).

$$W = \frac{c}{2 * f_r} * \sqrt{\frac{2}{\varepsilon_r - 1}} \tag{2}$$

$$L = 0.5 * \frac{c}{f_r * \sqrt{\varepsilon_r}} \tag{3}$$

Those initial values were optimized in order to obtain a resonance frequency at 60 GHz and to shift a higher order resonance mode above 80 GHz. Further, the antenna feed needs closer attention. The antenna is fed by a 50-Ω transmission line, but in such substrate with thickness of 200 μm and $\varepsilon_r = 9.8$, its width is almost as wide as the patch, and will reduce the overall antenna efficiency. Moreover, if we choose to feed the antenna by just connecting a 50-Ω transmission line to the border of the patch, an impedance transformer would be necessary to match theses impedances. The impedance at the border of the patch is about 400 Ω, thus the transformer line impedance would be around 140 Ω and its width would be close to the minimum dimension that the fabrication process could accurately produce. Therefore, a traditional quarter wavelength transformer is also not feasible. To overcome these issues, a slow-wave 50-Ω feed line was designed on a 50-μm nanowire-filled region of the MnM-substrate, which reduces considerably the width of this feeding line. In addition, a solution comprising an impedance transformer and inset feed was used, which reduces the impedance of the traditional line, enlarging its width to acceptable dimensions within the fabrication limits. The design was optimized using the EM simulator HFSS and the final dimensions, shown in Fig. 1 are: $W = 750\,\mu\mathrm{m}$, $L = 730\,\mu\mathrm{m}$, $W_{feed} = 15\,\mu\mathrm{m}$, $W_{tran} = 30\,\mu\mathrm{m}$, $L_{tran} = 800\,\mu\mathrm{m}$.

3. MANUFACTURING

Since the feeding line should be fabricated on a 50-μm MnM-substrate and the antenna on a 200-μm stack of four membranes, the antenna assembly consists of two parts: the MnM-substrate and a metallized silicon cavity. Nanowires were also used to connect the ground of the coplanar pads used for the measurement probes to the microstrip ground.

A single 50-μm-thick alumina porous membrane was used to fabricate the microstrip circuits: the patch antenna, the impedance transformer and the slow wave feeding line. The process sequence is described as follows, illustrated in Fig. 2. **1**- A porous membrane with 25 mm in diameter acquired from Synkera with 55-nm pores, spaced 150 nm apart, was boiled in trichloroethylene, then acetone and last isopropyl alcohol, for 5 minutes on each solvent, for cleaning. **2**- 1-μm silicon dioxide (SiO_2) was deposited by PECVD to be used as a mask. **3**- The SiO_2 was patterned by photolithography in the regions where the nanowires will grow and SiO_2 etch on BOE (buffered oxide etch). **4**- A copper (Cu) seed layer was deposited by sputtering. **5**- The nanowires were grown by Cu electrodeposition. **6**- SiO_2 and Cu seed were removed by mechanical polishing. **7**- 1-μm of SiO_2 was deposited by PECVD. **8**- The nanowire region for the ground pad was patterned. **9**- 50-nm Cu seed was sputtered and thickened by electrodeposition up to 3 μm. **10**- The circuit elements were patterned by photolithography and Cu etch with a solution of ceric ammonium nitrate and acetic acid.

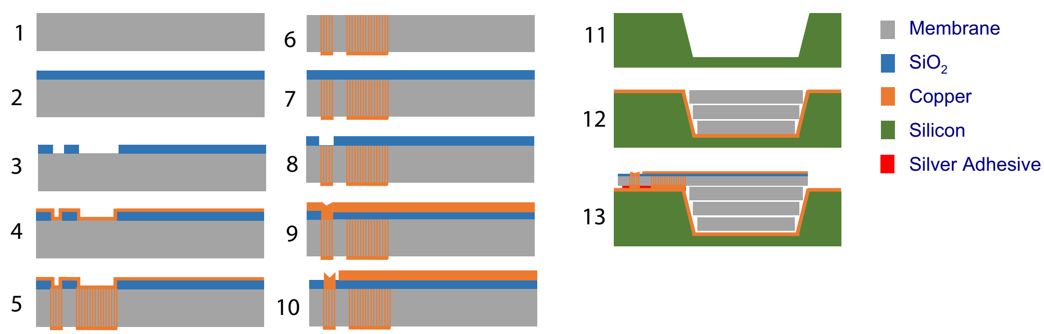


Figure 2: View of a transversal cut of the antenna presented in Fig. 1 with its fabrication process: (1–10) Steps of the microstrip devices. (11–13) Steps of the mechanical silicon substrate assembly.

11- A 150-μm deep cavity was etched in the silicon wafer with a potassium hydroxide solution (30% at 60°C) and covered by a Cu layer of 3 μm to act as the ground plane for the whole antenna. **12**- A bare membrane was cut using a LPKF laser system, and stacked into the cavity. **13**- A single patch antenna, also cut with laser, was aligned above the cavity. A silver conductive adherent was used to assure electrical contact between grounds (ground pad, slow wave 50-Ω feeding line, and antenna).

4. DISCUSSION AND RESULTS

The designed antenna structure was simulated and the results of return loss (S_{11}), gain, and radiation pattern are shown in Fig. 3. The simulated antenna presented 5.4 dBi of gain with 2.4% of 10-dB bandwidth.

Since the antenna gain is reduced with the increase of ε_r, any antenna fabricated on this substrate will present a lower gain compared to a similar structure fabricated on a substrate with lower ε_r. However, since passive elements size is also reduced by an increase of ε_r, any antenna fabricated over this substrate will also occupy a smaller area compared to a similar structure fabricated on a substrate with lower ε_r. The further miniaturization provided by the slow-wave effect present on the MnM-substrate means that a compact antenna array can be easily designed to increase the system gain. Beam steering techniques may also be achieved using integrated slow-wave phase shifters.

The loss tangent, $\mathrm{tg}(\delta)$, of the alumina and the SiO_2 is low enough to not affect the gain drastically. Simulations assuming a hypothetical worst-case scenario, assuming $\mathrm{tg}(\delta) = 0.001$ for both alumina and silicon dioxide, barely changed the gain. It is worth to note that optimization for losses and gain was not the focus of this work, but the antenna fabrication viability on the MnM-substrate.

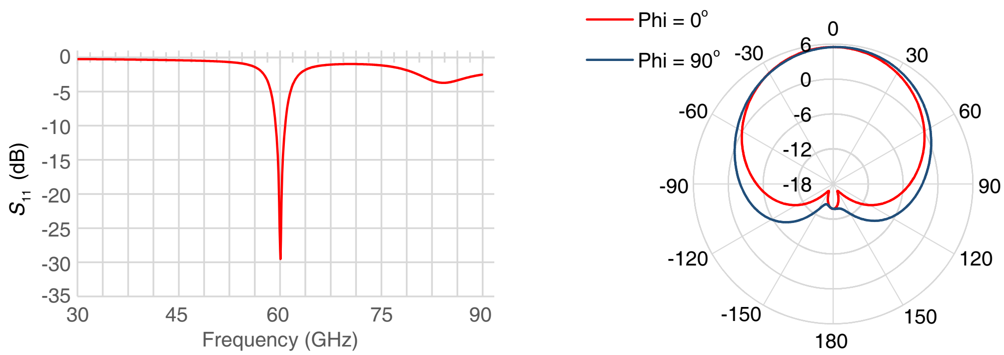


Figure 3: Simulation results for the designed antenna. (a) shows the frequency response of the return loss (S_{11}). (b) shows its radiation pattern at 60 GHz.

A simple improvement in this design would be to remove the alumina membrane from inside the cavity to reduce ε_r, which would increase the antenna gain, although its dimensions would also increase.

The fabrication process was successful and the fabricated antenna is shown in Fig. 4. This figure shows the silicon wafer on which the metallized cavities were etched. The detail in yellow shows the final antenna assembly, where a 50-μm-thick membrane bearing the antenna structure was aligned over the cavity filled with the three membranes-stack. The detail in blue shows the antenna structure with the patch, the impedance transformer, the slow-wave feed and the CPW pad.

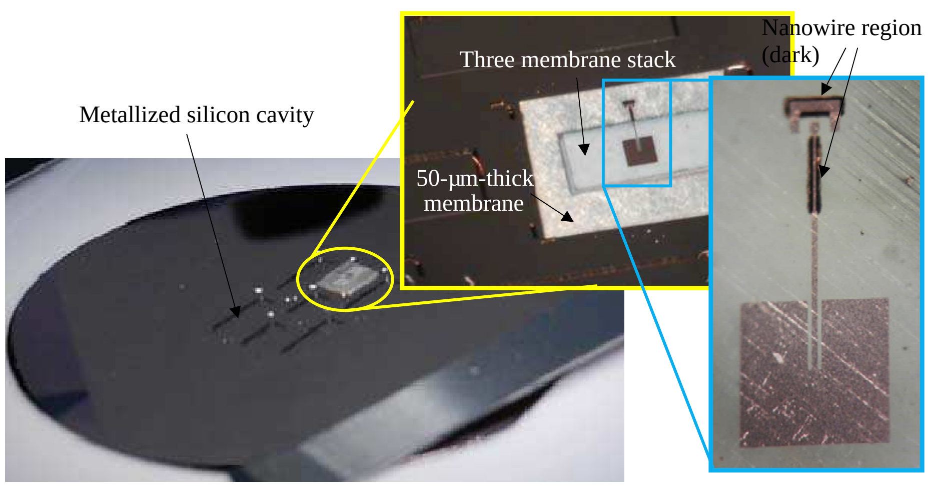


Figure 4: The fabricated 60 GHz antenna on the Mnm-substrate.

5. CONCLUSION

This work presented the analysis of the novel MnM-substrate for designing antennas at 60 GHz. The fabrication process of the rectangular patch antenna on the MnM-substrate was validated. The fabricated antenna was fed through a modified microstrip line with slow-wave effect, and the results indicated that this substrate is a viable choice for antenna design in mm-wave frequencies. However gain increasing techniques should be used because of the high dielectric constant of the substrate.

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