New Manufacturing Technologies For 5G Millimeter Wave Antennas

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Abstract—This paper shows the implementation of different manufacturing technologies for 5G millimeter wave applications. The first uses low-loss dielectric substrates for the design of antenna arrays, with low temperature cofired ceramics (LTCC) as high permittivity and low-loss material. Alternatively, designs are shown using fully-metallic structures based on 3D-printed gap waveguides to reduce losses and manufacturing cost.

Keywords—additive manufacturing, groove gap waveguide, millimeter-wave, metallized 3D-printed technology, aperture-coupled patch antenna, antenna array, LTCC, 5G mobile communication.

I. INTRODUCTION

Nowadays, more network capacity and connectivity are required, and also additional spectrum. Mobile networks have improved quality of service (QoS) by using higher frequencies and higher bandwidth. Therefore, it has been established that 5G will use a higher spectrum, for example, using the millimeter frequency band due to its considerable available bandwidth [1].

In order to meet the technological demand to address the commercial exploitation of the millimeter wave bands, it is necessary to develop new technologies and manufacturing techniques to achieve a reduction in the cost of mass deployment. Due to this, low-temperature cofired ceramic (LTCC) have been used in recent years because of their low losses at high frequencies, low cost and simple manufacturing process in multilayer circuits [2]. However, the use of dielectric materials still introduces unwanted losses that may be unacceptable for high frequency applications. Gap waveguide technology is being used in recent years to overcome these drawbacks with full-metal structures [3] using a lattice of periodic metallic pins. Its dielectric-free characteristic leads to low losses. Moreover, the technology was created to address bad electrical contacts between metal plates, which are a critical problem at high frequencies. The pins result in a high impedance surface over them that blocks propagation in a given frequency band. However, the implementation of this idea for real prototypes using conventional machining techniques supposes a high manufacturing cost of those pins. Focusing on that, additive manufacturing is a good alternative for this type of structures [4].

This paper presents several array antennas designed in PTFE substrate and LTCC at 60 GHz, together with manufacturing results in metallized 3D-printing of some Ka-band prototypes and new proposals for millimeter components designed to operate at 94 GHz.

II. ANTENNA DESIGNS USING DIELECTRIC SUBSTRATES

In this section we show two designs with different type of low loss substrates. The first one is a PTFE Rogers with low permittivity and the second one is based on LTCC with a high permittivity. A comparison between both designs is carried out.

A. PTFE Design

The proposed antenna element can be decomposed in three layers, as shown in Fig. 1. In particular, it consists of three commercial Rogers substrates, the patch and the microstrip feed line are physically printed in Rogers 5880, whose relative permittivity \( \varepsilon_r = 2.2 \) and the dissipation factor \( \tan \delta = 0.0009 \) at 10 GHz and Rogers 6010 with permittivity \( \varepsilon_r = 10.2 \) and dissipation factor \( \tan \delta = 0.0017 \) at 10 GHz respectively. The reason of using a high permittivity substrate for the feed line is to reduce the size of the feeding network, thereby mitigate the back radiation and the losses of the conductor. For the strongest bonding between two different materials, a prepreg Rogers 2929, with \( \varepsilon_r = 2.94 \) and \( \tan \delta = 0.003 \) at 10 GHz, is used to adhere this structure.

B. LTCC Design

A conventional aperture-coupled patch antenna is shown in Fig. 2. The substrate used is LTCC Dupont 9V7k, with \( \varepsilon_r = 7.1 \) and \( \tan \delta = 0.0009 \) at 10 GHz. The patch is printed on three layers of LTCC with each layer being 0.112 mm thick. The 50 \( \Omega \) microstrip feed line is designed on a single LTCC layer with width \( w = 0.13 \) mm. In order to reduce the coupling between radiating elements, a cavity is introduced in this design.

Fig. 1. Stack-up of Rogers design. Layers thickness are: Rogers 5880 - 0.127 mm, Rogers 2929-0.051mm, Rogers 6010 – 0.254 mm.

Fig. 2. Conventional aperture-coupled patch antenna designed in LTCC.
C. Array Configuration

To achieve greater gain, the radiating elements described in the previous sections are arranged forming 2x2 array antenna. The arrays are feed by multi-section T-dividers as shown in Fig. 3. The upper two patches are given 180-degrees phase rotation with respect to the pair below, instead of using an equal feeding phase approach.

Fig. 3. Feeding network of 2x2 array antenna.

Fig. 4 presents radiation pattern of 2x2 array antenna at 60 GHz using Rogers substrates (Fig. 4 (a)) and LTCC (Fig. 4 (b)). For this frequency, we have considered that the dissipation factor increases in a factor 10 compared to the value at 10 GHz for both materials. The maximum gains are 7.93 dBi and 10.3 dBi with total losses around 3.1 dB and 2 dB, respectively.

Fig. 4. 3D radiation pattern at 60 GHz of 2x2 Rogers design (a) and of 2x2 LTCC design (b).

Fig. 5 presents the $S_{11}$ parameter of the 2x2 array antennas. Despite the good properties of LTCC, the use of dielectric materials results in higher losses than fully-metallic designs. For this reason, designs without dielectric substrate have also been made using gap waveguide technology based on metal pins. To facilitate the manufacturing of these pins, a 3D printing process with subsequent metallization has been used. This process has been successfully applied to gap waveguide based structures [4]. Combining these two technologies in growing development, gap waveguide and additive manufacturing, it is possible to reduce the manufacturing cost of prototypes achieving very low losses with very good performance.

A. Metallized 3D-Printed Prototypes in Detail

Fig. 6 shows some structures printed on different plastic materials and with various metals. Images taken under an optical microscope from the circular pins and corners of the transitions to waveguide are included. It can be seen that the manufacturing precision is very good. In addition, the metallic coating applied on the 3D-printed models is very smooth, with a roughness measured with a profilometer of 0.3 µm rms. This value implies very low losses in the conductor, since roughness becomes the predominant factor for increasing losses at high frequencies.

Fig. 6. Printed details of Ka-band prototypes. The structures corresponds to several groove gap waveguide sections and power divider with WR-28 transitions. These prototypes are printed in different materials and plated with copper or aluminium. Images of a pin and the corner of the transition are taken using an optical microscope.

In view of the precision in the 3D printing process, W band component designs are proposed for technology validation.
B. GGW Components for Millimeter-Wave Band

Groove gap waveguide (GGW) has been selected because it provides lower losses than other gap waveguide alternatives [5]. The main design parameters are the diameter and height of the pins, as well as the air gap between these pins and an upper metal plate. Pins with 0.5 mm diameter and a height of 0.9 mm have been used to compose a 3.25 mm width waveguide with minimum losses and low dispersion at W band. The pins are placed periodically separated by a distance of 1.2 mm and on top of them a plate is placed 0.4 mm apart. In this structure only the TE$_{10}$ mode is propagated between 64.5 and 99 GHz. Fig. 7 shows some structures designed with the previous dimensions for frequencies around 94 GHz. These structures include a straight section, a power divider and a crossover. In [6], these elements are used to design a complete Butler matrix.

The designs in Fig. 7 will be used to create a Butler matrix for a radar at 94 GHz. Then, they have been optimized for that frequency, but it is interesting to achieve good matching in a wider band for availability in other applications and minimize effects due to manufacturing errors. Simulated and measured results of the three designs are shown in Fig. 8, 9 and 10. The flexibility of 3D-printing allows to manufacture complex structures like the WR-10 transitions of the models in Fig. 7 (b,c) to achieve a reflection coefficient below -30 dB from 85 to 100 GHz in simulation and around -20 dB in measurement as shown in Fig. 8. Considering a roughness of 0.3 µm rms in the simulations, the losses introduced by the 50 mm length straight section are 0.3 dB at 94 GHz, which fits very well with the measurements. The results for the power divider are depicted in Fig. 9. The measured reflection coefficient is worse than the simulated, but it still keeps around -20 dB in an 8 GHz bandwidth centered at 94 GHz. Measured losses matches very well with the simulation in the power divider prototype with a total length of 40 mm from input to outputs. Finally, the latest design presented in this paper is a crossover based on two 3dB-90° hybrids [7]. The results of the crossover are represented in Fig. 10. Reflection coefficient for the crossover is below -15 dB in a band about 6 GHz. The measured insulation achieved by the parallel port at the inputs and outputs (S$_{21}$ and S$_{31}$) is below -30 dB at 94 GHz in both cases. The transmission (S$_{11}$) behavior is very good, with great similitude with the simulation and around 0.5 dB of losses at 94 GHz for a total length of 70 mm.

Fig. 7. Manufactured designs using 3D-printing. Prototype with a straight section, a power divider and a crossover (a), detailed top (b) and bottom (c) views of the transition to WR-10.

Fig. 8. Simulated and measured S-parameters for the straight section.

Fig. 9. Simulated and measured S-parameters for the power divider.

Fig. 10. Simulated and measured S-parameters for the crossover.
IV. CONCLUSIONS

Planar antenna arrays are presented at 60 GHz with two different materials: LTCC and Rogers substrates. From the results of simulation, we can find that LTCC has a better performance at 60 GHz band, although it still has important losses. To address that, additive manufacturing applied to gap waveguide structures has provided very satisfactory results. Some 3D-printed prototypes have been shown in detail and various models of operating components have been proposed and measured in W-band. These designs would be very complicated and expensive to manufacture with a different technology than 3D-printing. Due to the extremely low roughness achieved in the metallization process, a loss of only 0.05 dB/cm is measured.

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