Substrate Integrated Millimeter-wave Antennas Operating at 60/140 GHz
(invited paper)

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Abstract

This paper reviews the applications of substrate integration technology in millimetre-wave (mmW) antennas at 60-GHz and 140-GHz bands. The main challenges of mmW antennas such as losses, bandwidth and measurement are addressed. First, the technology to reduce the surface-wave loss of an antenna array operating at 60 GHz is introduced which is integrated into low-temperature co-fired ceramic (LTCC). Then, a broadband technology is applied in a high gain 60-GHz LTCC array design is reviewed. Finally, the progress in the design and measurement of LTCC antenna arrays at 140 GHz is updated.

Keywords : Millimetre-wave, Antennas, Gain, Radiation Patterns, Measurement

1. Introduction

Millimeter-wave (mmW) bands, in particular, 60-GHz and 140-GHz bands, are becoming increasingly important in many applications such as radar, imaging, and communication systems due to their wide operation bandwidths. Antenna design at such high operating frequencies has arisen many challenges of not only the design methodology for high performance but also non-electrical issues such as mechanical fabrication tolerance, complexity, and cost. For commercial mmW systems, the substrate integrated planar antenna design has become attractive due to their low profile, easy integration into other circuits and low cost. For instance, mmW antennas fabricated on low temperature co-fired ceramic (LTCC) substrate are getting increasing attention due to its flexibility in realizing arbitrary number of layers. The reliable and flexible fabrication process of LTCC has offered much more design freedom such as cross-layer-vias, open and embedded cavities than conventional printed circuit board (PCB) process [1].

At mmW bands, there are several unique design challenges. Besides the cost and fabrication constraints, the high losses associated with antennas become much critical for desired gain [2]. The losses usually include ohmic losses caused by conductor and/or dielectric as well as surface wave losses. For example, the larger electrical thickness and the high permittivity of LTCC substrate used in antenna design result in significant losses at the mmW bands so that the low gain of the antennas and arrays on LTCC becomes a design challenge.

There have been the reported methods to suppress the losses caused by surface waves. The use of soft surface increased the achieved gain of an array structure by about 0.5 dB at 40 GHz for an 8×8 array at a price of the greatly increased areas of the antennas [3]. An alternative method is to partially remove the substrate surrounding radiating patches [4, 5]. Narrow trenches have been cut from the silicon around the radiating patch using micromachining process, and the substrate surrounding the radiating patches has been removed for suppressing the surface-wave losses. However, the abovementioned technique [5] can't be directly applied to the LTCC antenna designs due to fabrication constraints. Instead, a technique to partially remove the substrate surrounding the radiators was proposed, where the array can be formed using a normal LTCC process but higher gain has been achieved as reported in [6].

On the other hand, the broadband and high-gain design is the other challenge at mmW bands. For example, several countries have allocated 7 GHz of continuous unlicensed spectrum at varying bands between 57 ~ 66 GHz or 14.6% bandwidth. As a result, a design with an operating bandwidth of up to 15% is desired to cover all available bands. Here, a broadband LTCC antenna array with high gain and consistent radiation performance is introduced [7].

2. 60-GHz LTCC Antenna Arrays with Gain Enhancement [6]

The method to improve gain of an LTCC antenna array operating at 60 GHz is presented. By partially removing the ceramic surrounding the radiating edges of the patch elements in the arrays the surface waves is suppressed. The process conforms to the constraints of LTCC process at mmW frequencies as shown in Fig. 1, where a conventional aperture-coupled patch antenna operating at 60 GHz was fabricated on the substrate LTCC (Ferro A6-M with $\varepsilon_r = 5.9$ and a loss tangent of 0.001). LTCC layer is 0.09652-mm thick with totally five layers and an overall size of l=4 mm, w=4 mm, $h_1 = 0.38608$ mm, and $h_2 = 0.09652$ mm. The radiating patches were printed on the top layer and fed by 50-Ω feeding microstrip lines with a width $w_m = 0.15$ mm, printed on the bottom of the substrate, through a feeding slot cut onto the ground plane.

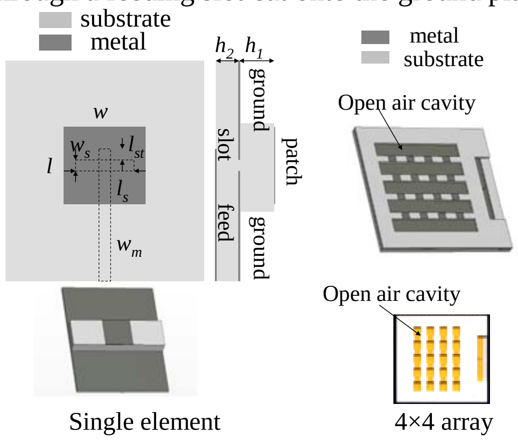

Fig. 1 Geometry of an element and a 4×4 array with partially removed substrate at radiating patch edges

The $|S_{11}|$ of the antenna arrays was measured using a Cascade Microtech Summit 11000 probe station and Agilent E8361A vector network analyzer as shown in Fig. 2 (left). The measured bandwidth for $|S_{11}| \leq -10$dB is 13% or 57-64 GHz.

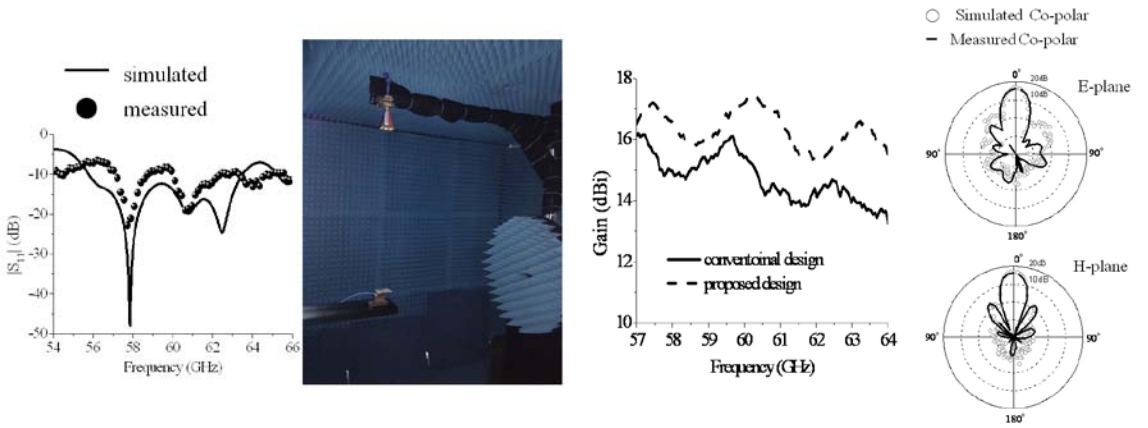

Fig. 2 The comparison of simulated and measured $|S_{11}|$, gain and radiation patterns of the proposed 4×4 array

The gain and radiation patterns were measured in a mini-chamber as shown in Fig 2(left). With the microstrip-to-GCPW transitions, the gain and radiation patterns were measured on-wafer, with the patch array facing upwards to free space, away from the antenna holder and probe station. For pattern measurements, the axis rotation are fixed but the probe feed and antenna position are changed to obtain the E- and H-plane cuts. The probe arms are connected to a straight and L-shape holder, respectively for the respective cuts. From the measured gain and radiation patterns of the proposed array as hsown in Fig. 2 (right), it is seen that the achieved gain of the proposed antenna has been 0.5-2 dB higher than the conventional design without any substrate removal. The simulated and measured radiation patterns are in a good agreement.

3. 60-GHz LTCC Antenna Arrays with Bandwidth Enhancement [7]

The technology to enhance the operating bandwidth of a substrate integrated waveguide (SIW) fed LTCC cavity array antenna is presented at 60-GHz bands. A 8×8 antenna array is designed to verify the design, where radiating elements, feed network, and transition have been optimized as shown in Fig. 3, where all the feeding structure and radiators have been integrated into a 20-layered LTCC with the same properties as the previous design.

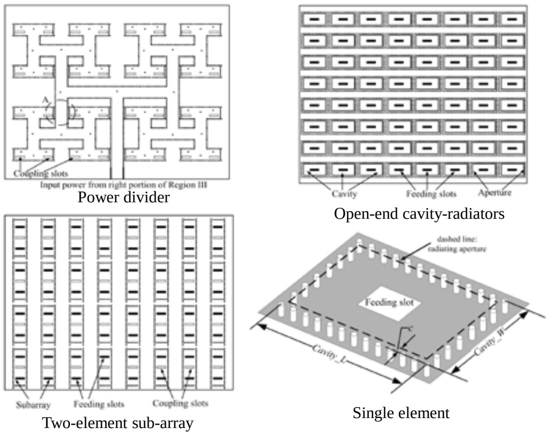

Fig. 3 The configuration of the proposed 8×8 array

Fig. 4 compares the measured and simulated $|S_{11}|$, gain and radiation patterns. The gain and radiation patterns were measured in a self-built mini-chamber as shown in Fig 2 (right). It is seen that the 8×8 array antenna achieved a wide bandwidth for $|S_{11}|$<-10 dB of 10.26 GHz (54.86−65.12 GHz) or 17.1%. A consistent gain response with a variation of 2.5 dB has been achieved over the operating bandwidth with the measured gain of 22.1 dBi at 60 GHz. The measured and simulated radiation patterns in both the E- and H-planes show the consistent direction of the mainlobe pointing to boresight and the side lobe levels of nearly -13 dB below the main beam over whole operating bandwidth due to the use of symmetrically parallel-fed network.

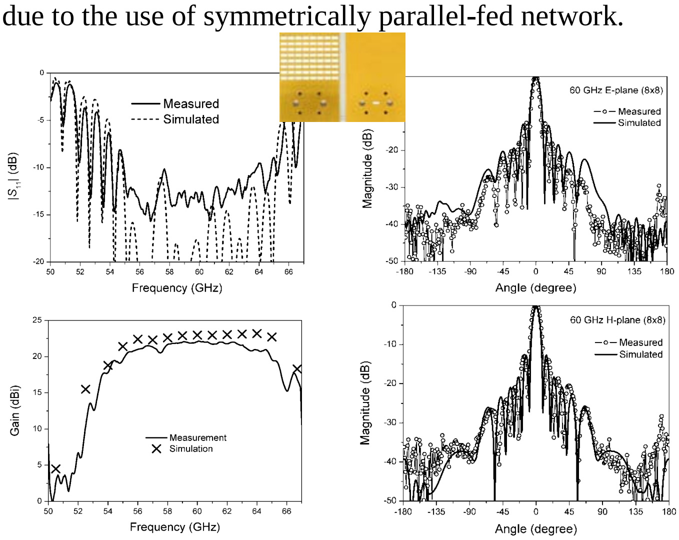

Fig. 4 Comparison of measured and simulated |S11|, gain and radiation patterns of the proposed 8×8 array

4. Design and Measurement of 140-GHz BCB/LTCC Antenna Arrays

The design, fabrication and measurement of antennas operating at D-bands (110-170 GHz) are much more challenging than ones at V-bands because of much shorter operating wavelengths. In Institute for Infocomm Research, Singapore, we have designed and measured several antenna arrays at 140-GHz bands.

A 2×2 patch array antenna has been designed and fabricated on benzocyclobutene (BCB) polymer. The antenna achieved an operating bandwidth of 131-140 GHz with gain of 9 dBi. Recently, a set of LTCC arrays operating at 140 GHz have been designed and measured with stable radiation patterns and high gain which are in a good agreement with simulated results. All the measurement of $|S_{11}|$, gain and radiation patterns was carried out at a self-built up mini-chamber as shown in Fig. 5, which was design for the measurement of radiation patterns and gain of on-wafer antennas operating at up to 325 GHz.

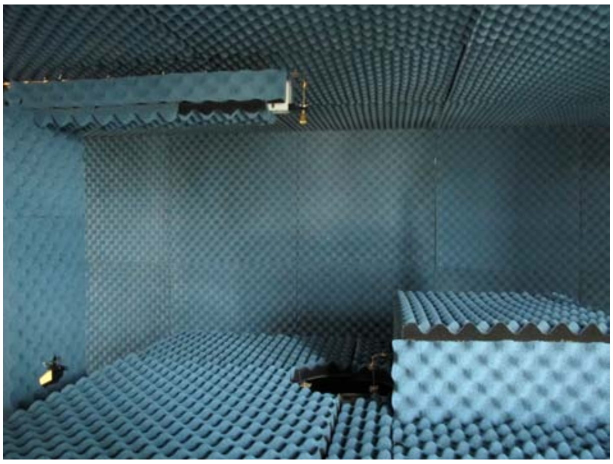

Fig. 5 A measurement setup for radiation patterns and gain of on-wafer antennas operating at up to 325 GHz

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