Simulating Process Variation Impact on the Performance of a mm-Wave Patch Array Antenna

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***Abstract*—** Millimeter-wave structures and circuits are susceptible to performance degradation due to fabrication tolerances. To avoid multiple fabrication iterations due to such unaccounted effects, it becomes imperative that the impact of process variations is taken into consideration during the design and simulation phase. This paper presents the use case of an E-Band microstrip patch antenna array's design, along with its simulation and measurement results, to demonstrate this scenario. This 4×4 antenna array was designed to operate in the 76-77 GHz frequency band and has a simulated -10 dB impedance bandwidth of around 2.6 GHz. As commonly seen with millimeter-wave designs, the post fabrication S_{11} measurements of this antenna showed a noticeable shift in its frequency response as compared to the simulated results. Here, Keysight's ADS RFPro full 3D EM simulation software was utilized to effectively predict the impact of manufacturing tolerances on the desired performance of the antenna. Parametric process variation simulations in RFPro revealed that there was an under-etching of copper on the printed circuit board during fabrication. This potentially resulted in changes to the physical dimensions of the individual radiating patches, thereby leading to a downward shift of the resonant frequency. These simulation results are further validated by means of measurements.

Keywords—antenna array, millimeter-wave, EM

I. INTRODUCTION

In recent years, automotive radar sensors have increasingly become an essential component in automobiles because of the benefits they bring like improved passenger safety, ease of driving, parking assistance etc. They provide useful information to a motorist about the presence of vehicles, cyclists, pedestrians, or any other potential obstacles in the vicinity by measuring the propagation time of electromagnetic waves from the radar source to the target and back. Millimeter-wave radar is particularly

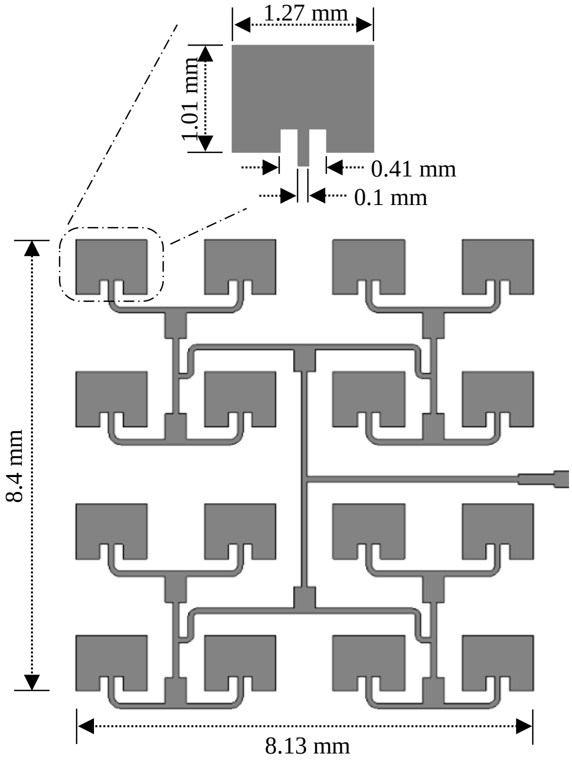

Fig. 1. Design geometry of the proposed 4×4 microstrip patch antenna array.

seen to be a key enabling technology for the successful operation of autonomous vehicles [1]. The focus in the development of automotive radar sensors mainly lies in the two allocated frequency bands of 76–77 GHz for long-range radar (LRR) [2] and 77–81 GHz for short-range radar (SRR) [3].

The performance of an automotive radar system is directly linked to its sensor antenna. The key requirements from such an antenna are to have a high gain, low sidelobe-level, compact size and a low profile [2]. Several antenna architectures such as slotted waveguides, microstrip patches, and reflector or lens-type antennas have been employed for implementing millimeter-wave automotive radar systems [3]. The microstrip patch antenna remains a preferred choice over several other antenna types due to its low profile, low-cost, easy manufacturability, and compatibility with printed circuit board technology [4, 5].

In this paper, a rectangular microstrip patch antenna array for 77 GHz automotive radar is presented, along with an investigative analysis for predicting the impact of fabrication tolerances on its performance. The antenna array comprises of 4×4 radiating elements and a corporate-type feed network. The array design was fabricated, and its simulation results were verified by means of measurements. The rest of the paper has been organized as follows. Section II discusses the design geometry and structure of the proposed antenna. In Section III, the simulated and measured results of the antenna are presented. Section IV provides details of the technique utilized to predict the effects of process variations on the desired RF performance of the antenna. Lastly, the concluding remarks for the paper have been provided in Section V.

II. Antenna Design and Configuration

A. Antenna Geometry

The geometry of the antenna array design proposed in this paper is illustrated in Fig. 1. The antenna is designed on a 0.127 mm thick Rogers RO3003 substrate with a relative permittivity of 3.07 and a loss tangent of 0.0011. The proposed antenna consists of 16 rectangular microstrip patches arranged in 4×4 array configuration for radiation, and a corporate feeding structure for exciting the patches. The radiating elements are the half-wavelength patches that are fed using an inset feed. The antenna array has been designed for a resonant frequency of 76.5 GHz. The width and height of each microstrip patch is 1.27 mm and 1.01 mm, respectively. The antenna array uses a 1 mm edge-mount coaxial connector from Southwest Microwave [6]. This is a 50Ω connector that provides mode-free operation up to a frequency of 110 GHz. It does not require any soldering to the antenna board and instead makes use of screws to snap on to the board. A prototype of the antenna array was fabricated and measured to verify its performance against its simulated results. Fig. 2 illustrates the fabricated prototype of the antenna array.

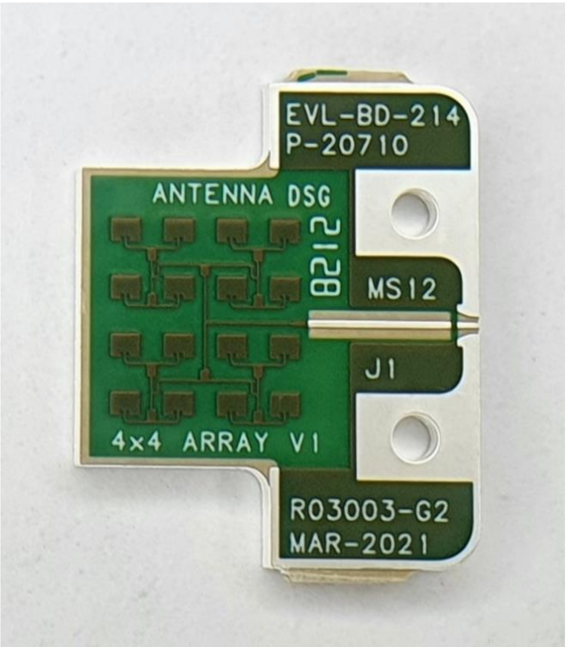

Fig. 2. Fabricated prototype of the proposed microstrip patch antenna array.

B. Feed Network

The radiating patches of the antenna array are fed by using a corporate type feeding network which excites all the antenna elements with an equal phase and amplitude. This feeding technique splits and distributes the input power equally to each individual radiating element. Quarter-wave impedance transformers are used in the feed network for impedance matching.

III. Simulation And Measurement

The 3D electromagnetic modelling and analysis of the proposed automotive radar antenna design was carried out using the Keysight Advanced Design System (ADS) RFPro [7] software package. The design was simulated from 70 GHz – 80 GHz using the full 3D Finite Element Method (FEM) solver in RFPro.

The input match (S_{11}) of the fabricated antenna was measured from 70 GHz - 80 GHz using Keysight's PNA-X [8] with frequency extender heads. The measurement reference plane was at the network analyzer's port. The antenna beam pattern could not be measured and is envisaged as future work.

A. *Return Loss*

The simulated return loss (S_{11}) in RFPro for the antenna design is shown in Fig. 3. The simulated resonant frequency is 76.5 GHz with S_{11} = -17.5 dB. The S_{11} is below -10 dB level from 75.2 GHz – 77.8 GHz, thus providing a -10 dB impedance bandwidth of around 2.6 GHz.

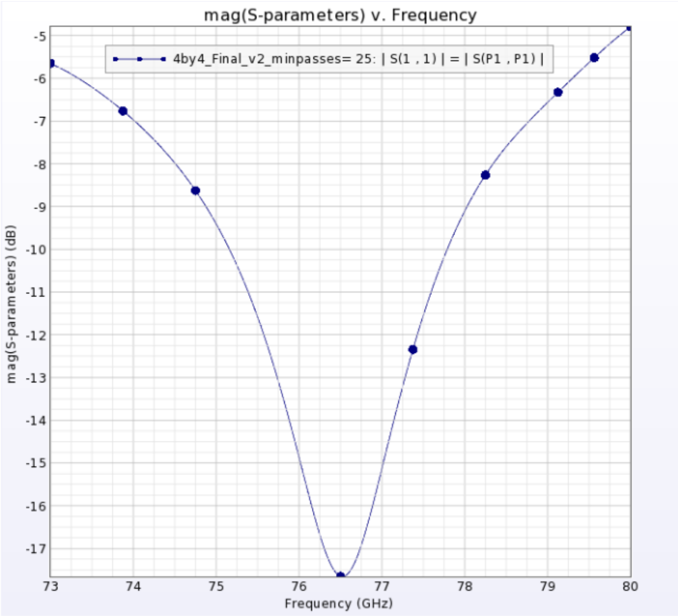

Fig. 3. Simulated Input Return Loss (dB) of the Antenna Array.

The antenna board mounted with a 1 mm coaxial connector was measured for its S_{11} performance at Keysight Labs in Germany. The PNA-X was set-up for 70 GHz – 80 GHz S-parameter measurements with frequency extender heads, as shown in Fig. 4. The measured results showed that there was a downward shift in the antenna's resonant frequency to 73 GHz, as illustrated in Fig.5. This led to further investigations into this performance variation, which are discussed in Section IV.

Fig.4. Measurement Set-up of the Antenna Board

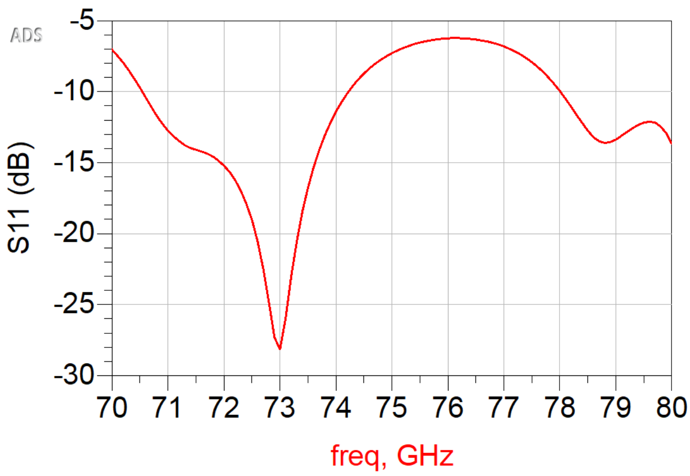

Fig.5. Measured S_{11} (dB) of the Antenna Array.

B. Radiation Pattern and Antenna Gain

The radiation pattern and antenna gain were obtained by means of RFPro simulations and the results are as presented in Fig. 6 and Fig.7. A peak gain of 17.2 dBi is obtained in the broadside direction at 76.5 GHz. The measurements for radiation pattern and associated peak gain could not be performed at this stage.

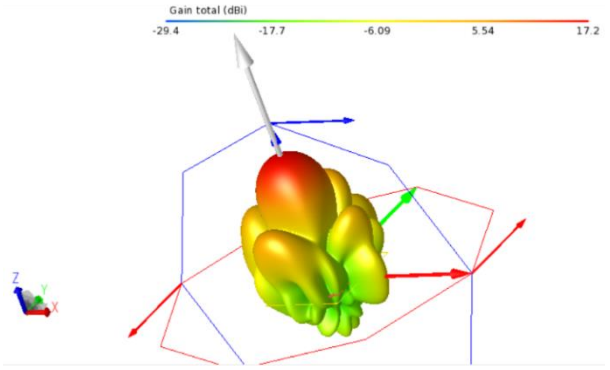

Fig.6. Simulated Radiation Pattern at 76.5 GHz

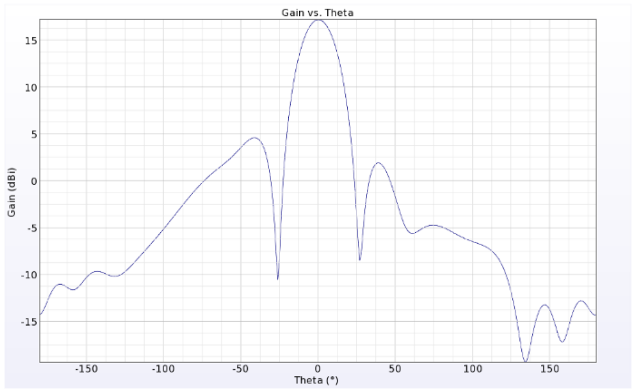

Fig. 7. Simulated Peak Gain in Broadside (dBi) at 76.5 GHz

IV. Effects of Process Variation

Millimeter-wave designs are highly susceptible to diverging from their desired RF performance due to fabrication tolerances, assembly variations for measurements, etc. This has been rightfully observed in this current E-Band antenna array's measured performance. Referring to Section III, it is observed that the measured resonant frequency of the antenna is shifted by around 3.5 GHz to the left as compared to the simulated results. In order to investigate the cause of this discrepancy in the simulated vs measured results, RFPro was utilized to set-up a process variation analysis. Various material parameters were set to change in a certain range to observe the effect of their variation on the antenna's simulation results. RFPro provides a seamless environment for setting up such swept analysis in an efficient way. The conductor (copper) etching was set to vary both for the under and over etching scenarios. From this analysis, it was found that a 15% under etching of the conductor material shifted the resonant frequency very close to the measurements (73 GHz), as shown in Fig.8. These results emphasize the fact that process variation effects should be considered during the design phase to avoid multiple design and fabrication iterations for mm-wave designs.

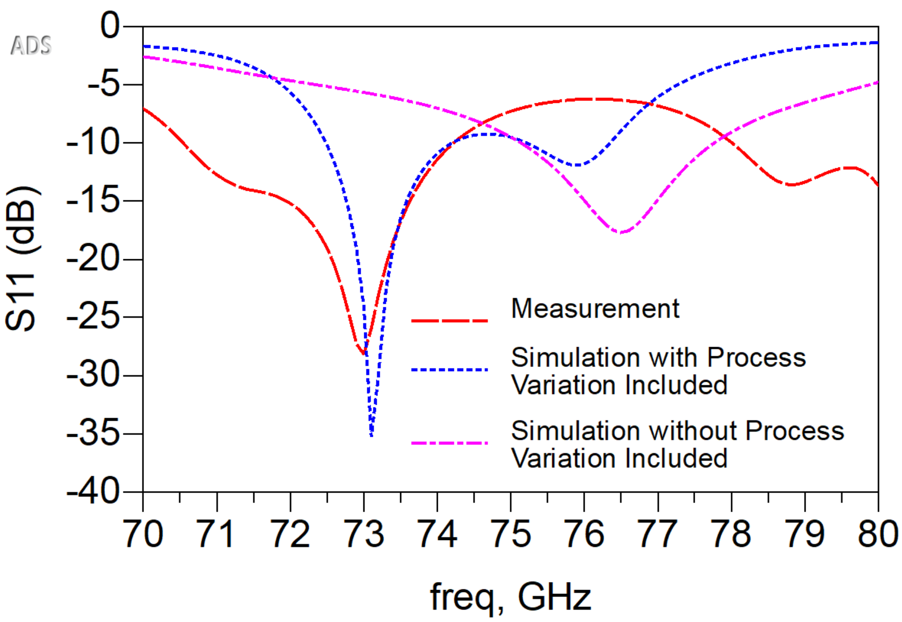

Fig. 8. Change in simulated S_{11} resonant frequency of the antenna array due to process variation which is verified with the measurement.

During the measurement process, it was also observed that even micrometer level of misalignment in the connector mounting on the board can lead to a significant deviation from expected results. This also re-affirms the high sensitivity of mm-wave designs to any external factors. Hence, thorough analysis and due diligence is required during the design, simulation and measurement phase of structures targeted to operate at such high frequencies.

V. Conclusion

In this paper, a 4×4 microstrip patch array antenna with corporate feed is proposed. The antenna is targeted for 77 GHz long range automotive radar. This 4×4 antenna array was designed to operate in the 76-77 GHz frequency band and has a simulated -10 dB impedance bandwidth of around 2.6 GHz. It was observed post fabrication that the S_{11} measurements of this antenna showed a noticeable shift in its frequency response as compared to the simulated results. A process variation analysis in Keysight's RFPro software helped in identifying the root cause of this shift in the measured frequency response. Conductor material under-etching led to a change in the dimension of antenna array's patches, thereby, resulting in the downward shift of the antenna's resonant frequency. Thus, it becomes imperative to perform process variation simulations during the design phase, especially for mm-wave structures to reduce design iterations.

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