Wideband Compact Comb-line Antenna Array for 79 GHz Automotive Radar Applications

Mohammad Mosalanejad, Student Member, IEEE, Ilja Ocket, Member, IEEE, Charlotte Soens, and Guy A. E. Vandenbosch, Fellow, IEEE

Abstract—A wideband microstrip comb-line antenna array is developed for 79 GHz MIMO radar applications. This array is composed of 4 radiating sub-arrays, with 180 degrees phase shift. This topology leads to a more stable radiation pattern behavior and broadside gain flatness along the frequency bandwidth. The antenna is taped out with a new high resolution multi-layer PCB technology, called “Any-Layer PCB”. This technology provides the possibility to stack small micro-vias, instead of using thick machine drilled vias. A measured impedance and gain bandwidth of 12.5% is achieved. The side lobe suppression is higher than 15 dB, and the array gain is 12.36 dBi at 79 GHz.

Index Terms—Comb-line antenna array, multi-layer PCB technology, millimeter waves, radar applications.

I. INTRODUCTION

MILLIMETER wave (mm-wave) technologies have been used in a variety of applications, such as communication systems [1], and millimeter wave radars [2]. MM-wave radar systems can detect presence, position, direction and relative speed of remote objects with small delays. The main driving force behind them is the automotive industry. 77/79 GHz radar sensors will soon be used in every car for enabling emergency braking systems [3].

Various antenna topologies are proposed in literature for 77-81 GHz automotive radar applications. In [4], a patch antenna array is presented, using a vertical parallel feed network. In [5], ceramic filled cavity resonators are used to make a planar antenna array. These two designs are made in LTCC (low temperature co-fired ceramic). Although the ideas behind these two papers are interesting, they have some issues. First, they are very costly to fabricate. Second, they have used a WR12 to laminated waveguide transition in the feeding mechanism, which is not compact and thus not suited for automotive radar systems. Finally, the design in [4] has a high gain ripple (5 dB) along the 77-81 GHz band, and the design in [5] is narrowband. In [6], hybrid multi-layer grid arrays are presented to reduce the cost. However, they have a very limited 3dB beam width (40

degrees in azimuth) and are by consequence not really applicable for medium and short range automotive radars. They also have very high SLLs at the band edge frequencies, and huge losses along the feeding network. It was already mentioned in literature that microstrip comb-line arrays are very good candidates for automotive radars, due to their wide impedance bandwidth [7]. In [8], [9] low side lobe comb-line designs have been achieved, using stub integrated radiation elements, and the stubbed element technique, respectively. In [10], the interesting idea of using reflection cancelling slit structures has been used to make the array more wideband. Even though all these designs have a wide return loss bandwidth and a good side lobe level (SLL) suppression at the center frequency, they have a big drawback: the high sensitivity of their radiation pattern to the frequency. Indeed, at frequencies away from the center frequency, the broadside beam squints about 1-2 degrees/GHz and the SLL degrades a lot. Further, MIMO radars have two main requirements. First, the cross talk between receiver and transmitter arrays must be mitigated as much as possible [11]. Second, the antenna width must be less than half a wavelength, to suppress potential side lobes as much as possible. None of the designs presented in [6]-[10] realizes these requirements.

In this paper, a compact comb-line antenna array topology for short or medium range MIMO radar applications is presented. A prototype antenna has been designed and fabricated with an advanced PCB technology. Unlike the topologies described in literature, it satisfies all the requirements needed in this type of applications.

II. PCB TECHNOLOGY

Multi-layer process technologies that can be used at mm-wave frequencies for integrating chip packages and antenna arrays are limited. LTCC is currently the most common and attractive one in industry. The main advantage associated with this technology is the high resolution in the manufacturing process. Its main disadvantage is that it is very costly and has a high manufacturing complexity [12]. In this paper, a new

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M. Mosalanejad and I. Ocket are with the Department of Electrical Engineering (ESAT), KU Leuven, and Inter-University Microelectronics Center (IMEC), Leuven B-3001, Belgium (e-mail: mohammad.mosalanejad@esat.kuleuven.be; and ilja.ocket@esat.kuleuven.be).

Ch. Soens is with the Inter-University Microelectronic Center (IMEC), Leuven, Belgium (e-mail: charlotte.soens@imec.be).

G. A. E. Vandenbosch is with the Electrical Engineering Department (ESAT), KU Leuven, Leuven B-3001, Belgium (e-mail: guy.vandenbosch@kuleuven.be).

Table I. Multi-layer build-up.

Material	Dielectric Constant	Tangent delta	Thickness (um)
Layer 8 (Comb-line array)			23
Sub7: Prepreg	3.26	0.01	68
Layer 7 (GND3)			16
Sub6: Prepreg	3.22	0.01	104
Layer 6 (Signal)			16
Sub5: Prepreg	3.22	0.01	104
Layer 5 (Signal)			23
Sub4: Core	3.37	0.01	100
Layer 4 (GND2)			23
Sub3: Prepreg	3.22	0.01	104
Layer 3 (Power splitter)			16
Sub2: Prepreg	3.22	0.01	104
Layer 2 (GND1)			16
Sub1: Prepreg	3.26	0.01	68
Layer1 (Microstrip line)			23

advanced PCB technology called “Any-Layer HDI” technology is used [13]. This technology delivers an accuracy close to the one of LTCC and the fabrication cost is less than one third. The main technical advancement of the Any-Layer technology over standard HDI PCB (High Definition Interconnect) technology [14] is that stacking micro-vias is possible. This allows to connect each layer or connection on a specific layer to every other layer within the PCB build-up. The huge restriction in the design process that laser drilled micro-vias used in HDI PCB technologies cannot be stacked is totally overcome. Further, note that conventionally drilled, blind, or through hole vias are created by machine drilling, which delivers a minimum hole and pad size of 200um and 400um, respectively. For laser drilled micro-vias, these values are 75um and 175um, respectively. This feature allows a higher routing density and a more compact size of the final PCB board. A comparison between LTCC and the Any-Layer PCB technology is given in Table II.

Table II. A comparison between Any-Layer PCB and LTCC.

Characteristics (um)	Any-Layer PCB	LTCC
Minimum substrate thickness	75	50
Minimum track width	40	35
Minimum micro-via diameter	75	50
Minimum clearance between tracks	40	35
Cost	Low	High

III. Array design

The design was performed by using Ansoft HFSS.

A. Multi-Layer PCB Build-up

The antenna layer build-up is shown in Table I. It is completely symmetrical along the substrate thicknesses. Eight metal layers, and seven substrates are used. All the substrates are chosen from Panasonic Megtron 6 [15]. It is worth mentioning that Panasonic has reported a tangent delta of 0.006 for this kind of substrates, but based on our measurements, the tangent delta is 0.01. The five middle substrates, substrates 2, 3, 4, 5, and 6 are the thickest ones to reach more bandwidth. The top and bottom substrates are chosen thinner to get an acceptable width for the transmission lines. Among the metal layers in the build-up, metal layers 2, 4, and 7 are the ground planes. Other metal

Fig. 1 (a) Regular comb-line antenna array, (b) compact comb-line antenna array.

layers in the build-up are reserved for the signal routing. Since in radar modules there are many digital and analog signal routings, the ground layers mitigate the interaction of different signal lines on each other. Furthermore, GND3 (layer 7) stops the waves radiated back to the build-up, which can completely destroy the radiation pattern.

B. Array Antenna and Design Procedure

The radiating mechanism of a comb-line antenna array is explained in [7]. In comb-line antenna arrays, the length of the radiators and interconnect lines must be close to half a guided wavelength, as shown in Fig. 1(a). The main problem associated to regular comb-line antenna arrays is the wide array aperture and by consequence the limited 3dB beam width. This is in contrast to medium and short range automotive radar requirements, which need a wide viewing angle of around 80 degrees in azimuth. In order to solve this problem, the antenna array shown in Fig. 1(a) can be subdivided, along the dashed line, and two sub-arrays can be made. By putting these two sub-arrays next to each other, and feeding them with a 180 degrees phase shift, a compact comb-line antenna array is achieved, as shown in Fig. 1(b).

The topology, cross section and dimensions of the array are shown in Fig. 2(a), (b). The array is composed of 4 sub-arrays, which are located at the top layer in the build-up. In classical series-fed antenna arrays, two phenomena occur: 1. the loss in the feeding network accumulates, and 2. the longer the array is, the more the phases of the feeding coefficients of the elements in the array depend on frequency. These two phenomena lead to a lower 3dB gain bandwidth. With the 4 sub-arrays in our topology, a more uniform current distribution on the sub-arrays is achieved, especially for the end elements, compared to the classical series fed case or the case with 2 sub-arrays. Another advantage of using the four sub-array configuration is that a balanced feeding structure along the direction of the array can be achieved. As both Feed 1 and Feed 3, and also Feed 2 and Feed 4 are symmetric with respect to the same axis of symmetry (i.e. the axis of symmetry of the entire array antenna), a stable beam can be achieved in a wide operating band. These advantages lead to a wider 3dB gain bandwidth. On the other side, of course, the more sub-arrays, the more complex the feeding network will be. Hence, 4 sub-arrays were checked to be an excellent trade-off between the array performance and the feeding network complexity. The

Fig. 2 (a) 3D view of antenna array, and topology and dimensions of stacked feeding micro-vias (b) array cross section and dimensions, (c) feeding network. CL=21.65mm, CW=2.31mm, Wpad1=0.25mm, W1=0.2mm, W2=0.05mm, L1=1.13mm, L2=1.25mm, D=1.2mm, D1=0.085mm, D2=0.13mm, Wpad2=0.205mm, Wpad3=0.25mm, L3=0.85mm, L4=0.72mm, W3=0.26mm, W4=0.1mm, L5=0.73mm, L6=0.66mm, W5=0.2mm, D3=0.425mm, D4=0.825mm, D5=0.5mm, D6=0.14mm.

distance between the top layer and GND2 layer (Ground of the array) is 376 μ m, close to about 0.18 wavelengths in the dielectrics. This distance helps us to reach more impedance bandwidth.

Each antenna sub-array is composed of 4 arms, connected with narrow transmission lines. The lengths of the arms and interconnecting transmission lines are optimized around half a guided wavelength to reach the best performance. The interconnecting transmission lines have opposite currents in adjacent sub-arrays, so that their

Fig. 3 (a) Return loss and gain ("RL" denotes Return Loss), (b) transmission coefficient spectra of feeding network shown in Fig. 2(c).

Fig. 4 Fabricated antenna.

spurious radiation is cancelled. The antenna sub-arrays are fed through stacked small micro-vias with 180 degrees phase shifts, as shown in Fig. 2(a). These micro-vias are fed through a power splitter embedded in layer 3. In Fig. 2(c), the power splitter including the strip lines and matching quarter wave lines are shown. It is worth mentioning that since 3 ground planes (GND 1, 2, 3) are used in the build-up, there is a high potential for parallel plate modes and surface waves to be excited. Hence, the antenna array is surrounded by a metallic cavity, implemented by stacked micro-vias. The metallic walls suppress the cross talk between the transmitter and receiver arrays significantly in the final MIMO radar module. The small micro-vias and their narrower pad size compared to machine drilled vias, help us make the antenna more compact. The cavity width is 2.06mm, which is very close to half a wave length in free space at 79 GHz. As mentioned in the introduction, both array size and cross talk suppression requirements are satisfied very well.

C. Simulation and Measurement

Fig. 3(a) shows the simulated and measured return loss, and gain versus frequency, including the feeding network shown in Fig. 2(c). It is worth mentioning that a transition from layer 3 to layer 1 is needed to physically connect the array feeding network to the chip. However, the impact of this transition is de-embedded from the actual measurement results in Fig. 3. The antenna is widely matched from 70 to 90GHz, regarding the simulation and measurement. The maximum gain is 12.36dB at 82GHz. In the band 77-81GHz, the maximum gain drop is less than 0.65dB. This feature is very important for

Fig. 5 Simulated and measured radiation pattern at (a) 77 GHz, (b) 79 GHz, (c) 81 GHz.

radar functionality since in the target detection procedure, a correlation between the transmitted and the received signal is performed. The more constant the spectrum is (from 77-81GHz) in the transmitter and receiver, the better the correlation is and a better target detection is achieved. Further, the gain has been measured from 74 to 84 GHz, where it shows a difference of less than 2.8 dB between maximum and minimum. Note that there is a discrepancy between the simulated and measured gain drop, 0.65 dB versus about 1.5 dB. It is hard to find a unique single reason for this. As far as we can see, this is due to a combination of factors: the fabrication tolerances on the geometrical and material parameters, which is worse than for LTCC, the accuracy of the gain measurement, etc. In Fig. 3(b), transmission coefficient spectra of the feeding network, between “Input” point, and “Feed1” and “Feed2” points (as shown in Fig. 2(c), are presented. This plot shows that the feeding network has a loss of around 1.25 dB between the input and output points. Further, note that the excitation amplitude in Feed 2 is about 0.2 dB higher than that for Feed 1. This is due to the longer feed line for Feed 1. However, this kind of phenomenon has no dramatic negative effect on the array performance since it is intrinsically incorporated in the optimization. It is worth mentioning that the simulated radiation efficiency (taking into account the losses in the feeding network) is 62%. A prototype of the fabricated antenna is shown in Fig. 4.

Fig. 5 shows the simulated and measured radiation patterns in the azimuth and elevation planes at 77, 79, and 81GHz. The

Fig. 6 Simulated and measured radiation patterns in H-plane at 75, 83, and 85 GHz.

simulated 3dB beam widths in azimuth and elevation are 124 and 10.5 degrees, respectively, which is according to the radar requirements for the automotive application targeted. Furthermore, the simulated and measured SLLs are -15.74dB and -14.36dB respectively at 79GHz. Pattern measurements have been done with the setup described in [16]. In Fig. 6, additional simulated and measured radiation patterns are shown at 75, 83, and 85GHz. From all patterns illustrated, it is clear that the SLL is under -13dB from 75GHz to 85GHz, (except for the measured pattern at 83GHz, which has a SLL of -12dB at one side), and that the broadside gain is less than 3dB lower than the maximum gain at 82GHz. This means that regarding reflection loss, 3dB gain bandwidth, and SLL this antenna can be used from 75 to 85GHz. This band corresponds to 12.5% of the center frequency. Further, it is seen that the simulated patterns at the frequencies 77, 79 and 81GHz are very similar to each other with almost the same SLL. This means that the pattern does not change with frequency, which verifies the flat gain behavior in Fig. 3. This is actually realized by the use of the 4 feeding points along the antenna array. Indeed, the more feeding points are used, the more uniform the current density is, and the better the radiation performance. It is worth mentioning that in contrast to the topologies reported in [8]-[10], no beam squint with frequency is observed in our design, thanks to the usage of the four sub-arrays with 180 degrees phase shifts. Indeed, a possible beam squint in any of the sub-arrays is cancelled by the other sub-arrays by the phase shifts. It must also be noted that in our design no tapering of the array arm widths is used, a technique sometimes used to improve the SLL [10]. Since the substrate thickness is large, it only has a slight impact and, moreover, it decreases the gain in the broadside direction. Hence, all the arms have the same width.

IV. CONCLUSION

A 16-element compact comb-line antenna array, composed of 4 sub-arrays, has been presented in this paper. The topology has a wide impedance and flat gain bandwidth. A prototype was realized in the high resolution advanced Any-Layer PCB technology. The measured results show an excellent agreement with the simulated ones. The topology is a very good candidate for 79 GHz medium and short range automotive radar applications, due to its low cost, compact size, the ability for surface wave suppression, and the wide impedance and gain bandwidth.

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