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Design considerations for the hot embossing of microstrip antennas on plastic foils

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In this contribution, fundamental design considerations for a novel metallization technique to realize millimeter-wave microstrip structures are presented. This hot embossing technology is a fast and economic process originating from the production of three-dimensional molded interconnect devices. Conductive structures are coated onto plastic parts or plastic foils using a heated stamp. This approach shows high potential and therefore will be investigated for the fabrication of low-cost printed antennas at millimeter-wave frequencies. The focus of this contribution is on design guidelines considering process parameters and interactions with substrate and copper foil characteristics derived from the fabrication and measurement of single microstrip patch antenna prototypes for radar applications in the industrial, scientific and medical (ISM) band at 24 GHz. Far-reaching potential lies in the utilization of the three-dimensional manufacturing technology for the construction of conformal integrated antenna systems based on the thermoforming capabilities of polymer substrates.

Keywords: Hot embossing, Metallization technique, Microstrip patch antenna, Low-cost fabrication, Molded interconnect devices

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I. INTRODUCTION

In the last decade the automotive industry has focused its efforts on developing a number of active and passive safety applications for traffic monitoring and collision avoidance. Automotive radar systems have become one key technology for driver assistance due to their weather independence, reliability in detection of range and velocity as well as integration possibilities behind electromagnetic transparent materials such as plastic car body panels [1]. Thereby the automotive radar market separates into the development of high-performance reconfigurable sensors embedded in versatile perception system architectures and stand-alone low-cost sensors for specialized applications such as pre-crash detection, collision mitigation, or parking aid [2]. Concerning the first sensor family, recent trends show that component suppliers are looking forward to bring the radar system and its functions into the midrange and compact class, where it could soon be part of a car's standard equipment. Improvement capabilities have been associated with packaging, silicon–germanium (SiGe) chip sets, and on-chip integrated antennas [3, 4].

While this first sensor family already entered the premium and upper-class car market years ago, the sensor price level still prevents functions for safety applications from the breakthrough in the compact class market. As an example, an integrated radar system at some exposed mounting places where bulky high-performance sensors fail could be a promising alternative to state-of-the-art externally visible ultrasonic sensors for parking aid if the price of the sensor could compete with the ultrasonic technology [2].

The outcome of this is hence the essential task for radar manufacturers to find hardware configurations at the lowest price level that fulfil the physical specifications for reliable sensor units. For the assembly of low-cost antennas, which could be embedded within plastic bumpers or car body panels, alternative polymer substrates and metallization techniques have to be found. In [5] a novel metallization technique for the ultra low-cost fabrication of microstrip structures on polymer substrates has been presented. This hot embossing process operates with a heated stamp, which is used to punch conductive paths from a copper foil into the surface of a plastic part. Basic microstrip antenna elements have been designed, fabricated, and measured, which show specific anomalies. In this contribution the hot embossing technology and further process steps are summarized and design guidelines resulting from process and material parameters are derived for novel prototypes aiming for the construction of conformal integrated antenna arrays.

II. HOT EMBOSSING TECHNOLOGY

A) Principles of the fabrication

The hot embossing process has been developed for the functional metallization of three-dimensional molded interconnect devices (3D-MID) with applications basically in the automotive and automation sector for the miniaturization and cost reduction of DC and low-frequency circuit boards. In comparison to other MID metallization techniques such as laser structuring or photolithography, hot embossing has the advantages of very simple and few design steps, low investment costs, and inexpensive design revisions. The procedure starts by milling the layout of an electronic circuit into a

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piece of tool-steel to form a stamp pattern. A chemically roughened adhesive-free copper foil is placed on a polymer substrate, Fig. 1(a), and pressed on it with the stamp at an increased temperature, Fig. 1(b). Under the influence of pressure and temperature the conductive lines are punched out of the metal foil and get connected with the thermoplastic substrate. The remaining foil breaks at the edges of the milled structure and is removed through the release of the stamp shown in Fig. 1(c). As an effect of hot embossing, the microstrip structure will show some special anomalies in comparison to standard photolithography boards. Due to pressure and temperature the polymer matrix is softened, resulting in better adhesion between copper foil and plastic part but also displacement of the polymer directly underneath the embossed structure. The substrate material is squeezed sideways and builds bulges as shown in Fig. 1(d). The resulting bulge height has only a minor influence on the performance of the microstrip line in contrast to the decrease in substrate height due to embossing depth, which results in lower line impedance and has to be considered in subsequent design steps.

B) Material properties

For the fabrication of 3D-MIDs, suppliers use various materials to which they have adapted their manufacturing processes. Basically, high-temperature thermoplastics are used. The key material properties to be considered are processing and usage temperatures, required flammability rating, mechanical and dielectric properties, mold and palatability as well as cost. The hot embossing process is especially applicable to the treatment of poorly metallizable polymers such as polycarbonate (PC) or blends with additives such as polybutylenterephthalate (PC + PBT) and acrylnitril-butadienstyrol (PC + ABS). In [6] PC and PC + ABS have been investigated concerning their mechanical properties for the fabrication of circuit boards with substrate heights of 250 µm. The dielectric properties of different polymer substrates were measured with transmission/reflection and open resonator techniques [7].

The copper foils for hot embossing need some particular properties. They must have high tensile strength and high brittleness as well. Furthermore, the copper foil needs different finishes on both sides. On the top side normally a protection layer against oxidization is applied suitable also for soldering assemblies. This aspect of top side treatment will be the focus of future contributions. On the bottom side the foils have to be roughened to guarantee adhesion on the thermoplastic. Common techniques are chemically roughened or black oxide treated surfaces. To reduce conductive losses of the microstrip lines, chemically roughened copper foils are advantageous in comparison to black oxide layers. The measured roughness values of the copper foil used in the following section are $R_A = 160$ and $R_Q = 207$ at a thickness of 18 µm. Figure 2 shows a SEM micrograph of the so-called cauliflower structure due to its bouquet-like surface. During processing the distant structures penetrate the softened polymer surface and anchor copper foil and substrate to guarantee high adhesion, as shown in Fig. 3. The disadvantage of the roughened surface is an increase in the attenuation constant. For a 50-Ω microstrip line on PC + PBT, the attenuation constant was measured to 21.4 dB/m in comparison to 13.8 dB/m for an equivalent line on Rogers 3003 substrate.

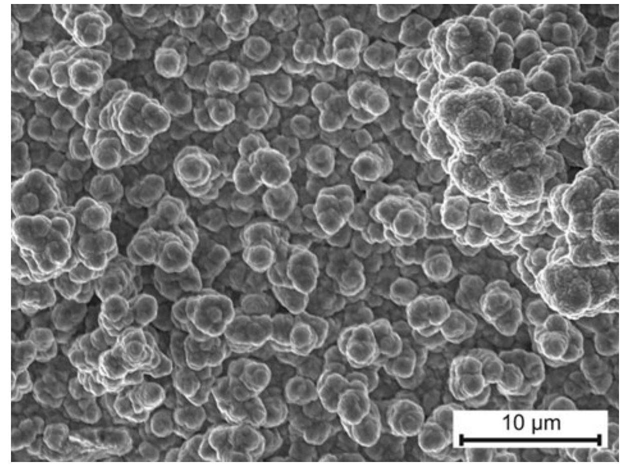

Fig. 2. SEM micrograph of the chemically roughened copper foil (cauliflower structure).

C) Process steps and parameters

The functionalization of polymer substrate surfaces with hot embossed conductive paths is basically associated with the trade-off between reliable adhesion of the metallization and low surface defects of the substrate due to warping or local surface-fuse. While adhesion can be improved by higher process temperatures and contact times of the stamp, the defects will increase at the same time. Apart from adequate

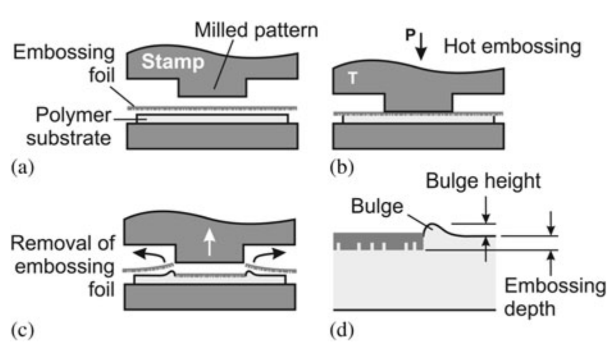

Fig. 1. Principles of hot embossing technology: (a) molding press arrangement, (b) hot embossing with pressure P and temperature T, (c) release of the stamp and removing the embossing foil, and (d) process anomalies of the microstrip lines.

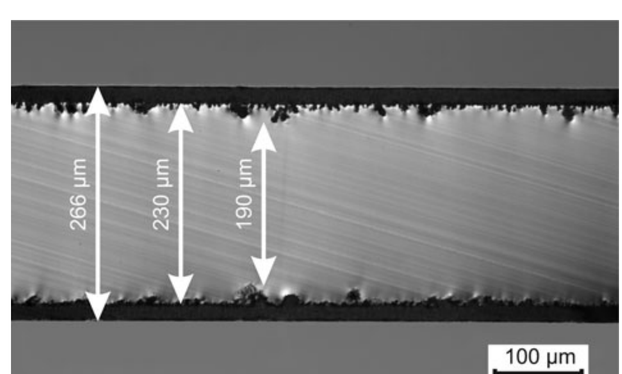

Fig. 3. Cross-section of the double-sided hot embossed polymer substrate.

removing properties of the embossing foil and low bulge heights, the adhesion of the metallization is the basic figure of merit. The determination of material-specific process boundaries is the scientific challenge of the hot embossing of very thin plastic foils.

The following results were achieved with the four-columned experimental embossing station from Blue Tiger Systems with a tensile and compressive force of 100 kN relocated over 100 × 100 mm². Hot embossing studies on 250-μm-thick polymer foils of PC, PC + ABS, and PC + PBT were performed. Due to the low substrate heights, slight warping of the samples could never be completely avoided. Because of its rigidity the metallization of PC foils affords higher temperature and pressure to achieve adhesion values of 0.35 N/mm measured in a common peel test with line widths of 1 mm. The process window of PC is therefore relatively narrow. For embossing times from 0.5 to 2.0 s the temperature must lie between 195 and 200°C with an embossing pressure of 70–90 N/mm² shown in Fig. 4. PC + PBT and PC + ABS in comparison show that by the addition of blend components the adhesion can be improved to 0.8 N/mm. In Fig. 5 the process window for PC + PBT is shown. Generally, a minimum embossing pressure of 50 N/mm² for removing the embossing foil and a minimum temperature of 175°C for optimum adhesion are required. The figure shows the process windows of embossing times between 0.5 and 2.0 s lying upon each other. The smallest window for 2.0 s is limited to 60 N/mm² and 180°C, causing deformations and local surface-fuse above these values. The broadest window for 0.5 s covers temperatures from 175 to 200°C and pressures from 50 to 90 N/mm². Altogether the metallization of PC + ABS and PC + PBT substrates can be accomplished with more gentle temperatures and pressures in comparison to pure PC substrates.

In a second process step depicted in Fig. 6, the ground plane for the microstrip configuration was applied by compressing the bottom side of the polymer substrate with an additional copper foil of the same physical properties with a pattern-free stamp. To compensate for the bi-metal effect due to the different thermal expansion coefficients of polymer and metal, an additional polymer layer below the ground metallization was inserted in the press. During the cooling of the specimen after this compression step, an unbalanced structure would drastically warp the sample. The balanced structure with polymer foils on both sides of the full plane metallization guarantees a uniform temperature expansion and therefore no deformations. The copper foil is only one-sided roughened and flat on the back side, so that the additional plastic layer can afterwards easily be peeled off. Figure 3 depicts a cross-section of the resulting microstrip line with an overall height of 266 μm, a substrate height of 230 μm, and distant structures with lengths up to 20 μm penetrating the polymer layer on both sides.

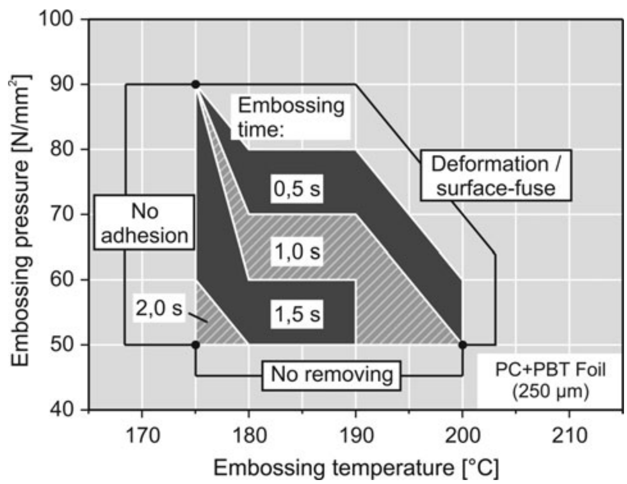

Fig. 5. Embossing process window for PC + PBT foil admitting adhesion of the conductor lines above 175°C, removing the embossing foil above 50 N/mm², and no deformation or local surface-fuse of the polymer below 90 N/mm² and 200°C.

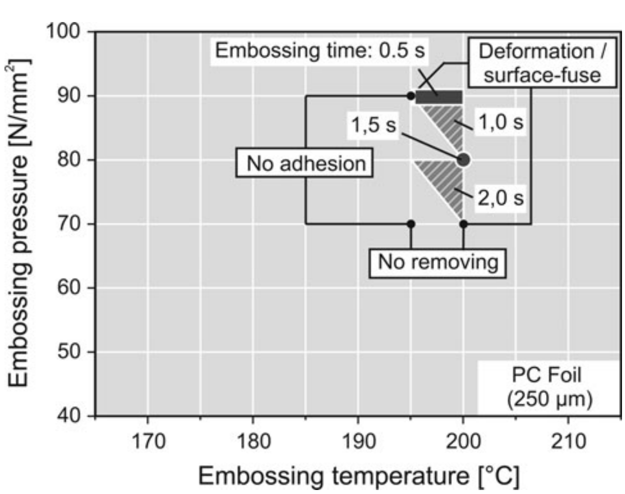

Fig. 4. Embossing process window for PC foil admitting adhesion of the conductor lines above 195°C, removing the embossing foil above 70 N/mm², and no deformation or local surface-fuse of the polymer below 90 N/mm² and 200°C.

III. DESIGN CONSIDERATIONS FOR MICROSTRIP ANTENNAS

A) Design, fabrication, and measurement of prototype structures

For the investigation of the hot embossing process including reproduction tolerances of typical geometries, three different

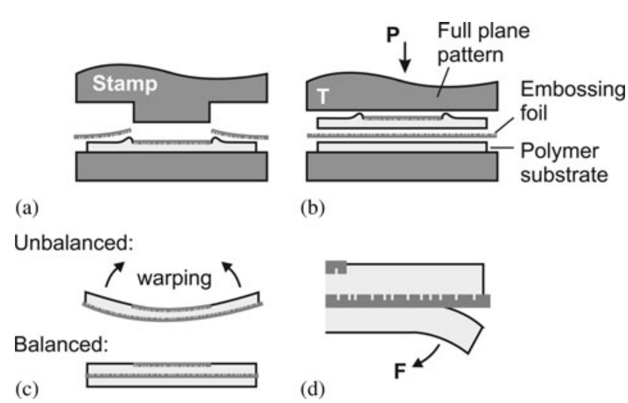

Fig. 6. Fabrication with post-processing: (a) result of the first hot embossing step, (b) compression of the ground plane with a full plane stamp pattern and an additional polymer foil below, (c) bi-metal effect of the unbalanced structure during cooling, and (d) removing the foil with force *F*.

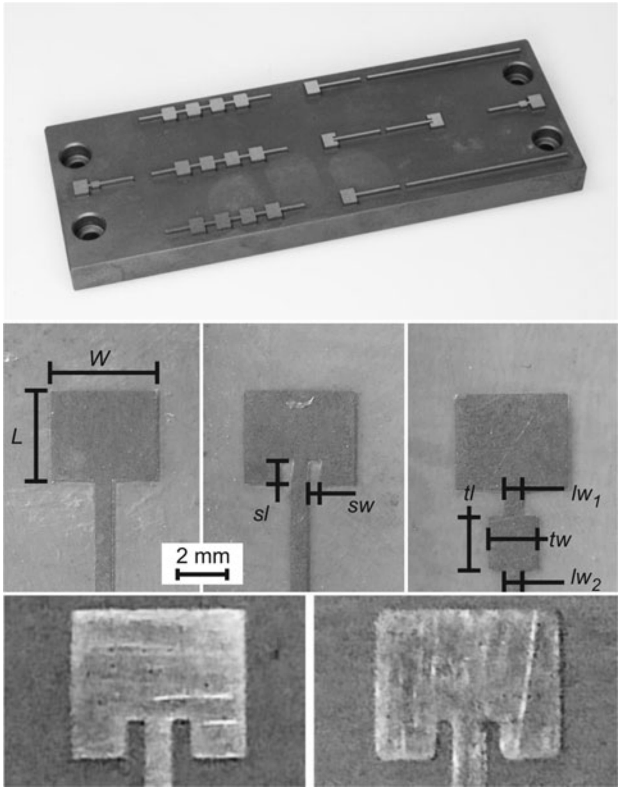

Fig. 7. Experimental stamp with embossed test structures (top), hot embossed single microstrip patch antennas with line feed, inset feed, and quarter-wave transformer feed (center), and patch with rectangular and chamfered edges (bottom).

single microstrip patch antennas were designed, a simple line feed, an inset feed, and a quarter-wave transformer feed configuration shown in Fig. 7 (center). Therefore, a substrate height of 250 μm and a relative dielectric constant of 2.6 for the polymer were assumed. Originating from reliable fabrication guidelines for hot embossed structures on arbitrarily shaped plastic parts, every antenna has been designed with rectangular and chamfered edges with a curvature radius of 250 μm depicted in Fig. 7 (bottom). Chamfered edges are advantageous concerning the removing of the copper foil during the release of the stamp and are commonly used for the fabrication of DC circuits. The dimensions for the layout of the first stamp are listed in the 'design' columns of Table 1. The stamp in Fig. 7 (top) has been milled from a block of tool-steel with a standard milling machine, afterwards hardened, and ground down to guarantee a planar surface across all structures. The dimensions of the resulting embossing patterns are listed in the 'stamp' columns of Table 1. The patches and the quarter-wave transformer show differences in the range of 25 μm. Basic problems arise from milling thin bars for the embossing of microstrip lines, and the line widths are up to 55 μm thicker. Occasionally the copper foil could not be completely removed from the inset feed surface, resulting in residues at these points. Concerning reproduction tolerances between the stamp and metallization, a general reduction of pattern widths in the range of up to 40 μm was measured. Obviously, the copper foil does not break directly at the edges of the stamp, but rather at the inside of the embossing structures. The edge structure being either rectangular or chamfered did not show any influence on the breaking abilities of the copper foil.

The original design for the stamp patterns was designed for radar application in the ISM band (24.0–24.25 GHz), neglecting fabrication tolerances due to milling and reproduction tolerances originating from the hot embossing process. In Fig. 8 the simulation results for the return loss of the hot embossed antennas with the actual measured dimensions (see 'structure' columns in Table 1) are depicted. The simulation model also included the decrease of substrate height and a relative dielectric constant of 2.75 for the PC + PBT polymer used in the investigated fabrication cycle. For the measurement results, the devices were inserted into a microstrip test-fixture and calibrated with through, reflect, line (TRL) standards. The comparison of the different configurations shows that for the line feed patch antenna the deviation of resonance frequency is about 100 MHz and the frequency shift for the other considerably better matched antennas is in the range of 550 MHz. Therefore technological dispersion lies in the range of 2–3%. The 10-dB return loss bandwidth was measured to be about 500 MHz corresponding to 2.1%. A cross-comparison with microstrip structures fabricated by a standard photolithography process on a familiar Rogers substrate did not show any evidence of discrepancies concerning the implemented design and simulation procedure.

B) Resulting preconditions and parameters

Concerning the geometrical dimensions of fabricated microstrip antennas, appropriate samples were investigated. The resulting embossing depth for plastic foils of 250 μm thickness lies in the range of a copper metallization of 20 μm. Bulges due to the squeezing of the polymer matrix below the stamp could be completely flattened during the second compression step with the full plane pattern. In future revisions the stamp has to be milled with even higher accuracy especially for the line widths. Conditional of manufacturing, the metallized

Table 1. Geometrical dimensions of the antenna design, stamp pattern, and hot embossed antenna structures in millimeters.

Dimensions	Line feed patch			Inset feed patch			Quarter-wave transformer feed patch		
	Design	Stamp	Structure	Design	Stamp	Structure	Design	Stamp	Structure
L	3.7	3.688	3.683	3.75	3.745	3.747	3.75	3.745	3.729
W	4.5	4.501	4.498	4.5	4.475	4.482	4.5	4.498	4.479
lw_1	0.66	0.695	0.683	0.66	0.69	0.67	0.66	0.715	0.699
sl/tl	—	—	—	1.0	1.03	1.024	2.1	2.12	2.082
sw/tw	—	—	—	0.5	0.51	0.503	1.9	1.917	1.899
lw_2	—	—	—	—	—	—	0.66	0.705	0.696

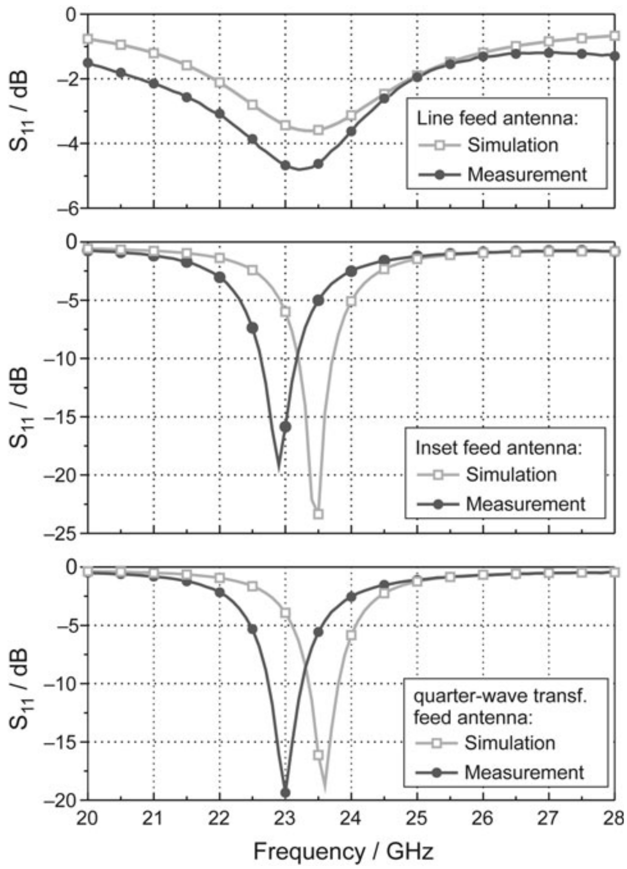

Fig. 8. Simulated (according to fabricated geometries) and measured return loss results for the single patch with line feed (top), inset feed (center), and quarter-wave transformer feed (bottom).

structures are reduced up to about 40 μm in comparison to the stamp pattern which also has to be considered in the layout of the embossed structures. The minimum substrate thickness where local surface-fuse and deformations can be compensated for by proper process parameters was determined to 250 μm. Actual results prove that even at this height deformations can never be completely avoided. By increasing substrate thickness, these side-effects can be considerably reduced.

Comparing hot embossed microstrip components with state-of-the-art structures on commercially available substrates like Rogers 3003, we conclude that the attenuation constant will rise due to the cauliflower-like copper foil surface. The peel strengths measured in a common peel test with line widths of 1 mm show that values of 0.8 N/mm^2 can be achieved, which compete with Rogers hydrocarbon ceramic compositions but fall below top values of 4.0 N/mm^2 for PTFE glass fiber materials. A decrease in surface roughness to diminish the attenuation would go along with peel strengths below this quality.

The decrease in resonance frequency occurring at the inset and transformer feed antennas can so far only be explained by an increase in substrate dielectric constant. Probably the polymer matrix is compressed below the stamp pattern in a way that the polymer chains reassemble and induce an increase in permittivity. This aspect has not yet been proved requiring the construction of a hot embossed sample that fits into the permittivity measurement set-ups available such as the open resonator or the filled waveguide section. The possible increase in dielectric constant lies in the range of 0.13 and could also be compensated for in future design revision steps.

IV. CONCLUSION

For automotive radar systems to be established at the middle and compact class market, ultra low-cost sensor units that nonetheless fulfil the physical specifications for target detection as well as range and velocity acquisition have to be designed. One aspect could be the integration of antennas into plastic car body panels and hence minimization of radar front-end fabrication costs. In this contribution design considerations for a novel metallization technique of polymer substrates have been investigated and optimized for the assembly of ultra low-cost millimeter-wave antennas. Single microstrip patch antennas have been designed, fabricated, and measured. According to the process steps and material properties, certain restraints have to be accounted for in future design revisions. The hot embossing technique has proven to be an attractive alternative to laser or photo lithography processes when process anomalies and inaccuracies can be compensated for by proper process optimization and design, including tolerance margins. Future steps will follow concerning broadband array antenna design, packaging, and system integration strategies. In addition, the manufacturing process shows great potential for the construction of conformal antennas by thermoforming metallized polymer foils and will be investigated in this respect.

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Lorenz-Peter Schmidt received his diploma and Ph.D. degree in electrical engineering from the Technical University of Aachen, Germany, in 1974 and 1979, respectively. From 1974 to 1979 he worked at the Technical University of Aachen as a research assistant, dealing with the analysis of transverse discontinuities in microstrip lines. In 1979, he became a post-doctoral research associate at the University of Texas at Austin. From 1980 to 1998, he was with AEG-Telefunken, Ulm (later DASA, now EADS), where he later became the head of the corporate advanced microwave and millimeter wave development department. His R&D activities included GaAs MMIC design up to 100 GHz, millimeter-wave interconnect and packaging technologies, radar sensors, transceiver front-end technology, and antennas and in the range 10–100 GHz. Since 1998, he has been a full professor and head of the Chair for Microwave Engineering and High-Frequency Technology, University of Erlangen-Nuremberg, Germany. His main research interests are in the field of millimeter-wave and terahertz components and antenna technologies as well as in active and passive imaging systems, laser technology, and microwave/photonic interaction. In 2003 he served as the General Chairman of the European Microwave Week and the Chairman of the European Microwave Conference in Munich, and is the German representative in the EuMA General Assembly. He is a member of VDE and chairman of the VDE/ITG expert group on Microwave Techniques, Senior Member of the IEEE, and member of the German IEEE MTT/AP Chapter Commission.