Institute of Microwave
and Wireless Systems

Leibniz
Universität
Hannover

2016 12th International Congress Molded Interconnect Devices (MID)

LDS manufacturing technology for next generation radio frequency applications

A. Friedrich
B. Geck
M. Fengler

Suggested Citation:
A. Friedrich, B. Geck, and M. Fengler. LDS manufacturing technology for next generation radio frequency applications. In *2016 12th International Congress Molded Interconnect Devices (MID)*, pages 1–6, Sept 2016.

Digital Object Identifier (DOI): 10.1109/ICMID.2016.7738939

This is an author produced version, the published version is available at `http://ieeexplore.ieee.org/`

©2017 IEEE Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works."

LDS Manufacturing Technology for Next Generation Radio Frequency Applications

A Discussion on Requirements and Solutions

Aline Friedrich[1,a], Bernd Geck[3,a]
[a]Institute of Radiofrequency and Microwave Engineering
Leibniz Universität Hannover
Hannover, Germany
friedrich@hft.uni-hannover.de

Malte Fengler[2,b]
[b]LPKF Laser & Electronics AG
Garbsen, Germany
malte.fengler@lpkf.com

***Abstract*— This contribution is focused on Laser Direct Structuring (LDS) fabrication for upcoming generations of RF-applications covering millimeter-wave frequencies. Starting with a short motivation the current situation of LDS fabricated RF devices is presented. Subsequently, the requirements on the manufacturing process for future applications are defined. The main LDS manufacturing parameters and their influences on the RF properties are discussed. Especially the influence of the surface roughness of the applied metalization is considered and evaluated. On the example of a millimeter wave dielectric antenna operating at 24 GHz and 77 GHz the suitability of LDS fabrication is verified. An RF characterization of the test antennas is done and the results are discussed. On basis of this, possible applications, in the automotive as well as consumer sector, are pointed out. Summarizing the main findings of this contribution the next steps to be taken for a fabrication of future LDS MID RF devices are derived.**

Keywords—laser direct structuring; molded interconnect devices; dielectric horn antenna; millimeter wave

I. INTRODUCTION

The Laser Direct Structuring (LDS) is a method to manufacture MIDs that is already common for efficient and flexible antenna fabrication in several applications, primarily in the consumer market. The operating frequencies ranges covered by these devices are typically below 6 GHz. Wireless connectivity is one of the main topics influencing our daily life and still gaining influence. On basis of different communication standards, devices like laptops, mobile phones or tablets are connected to its surrounding allowing transferring the user's data. In future the need for higher data rates and flexibility in data transmission indicates, inter alia, an increase of the operating frequency range for the following generations of RF systems [1]. On the one hand, the frequencies will decrease to lower frequencies like it is determined in the digital dividend II. This means that the associated wavelengths increase. Due to the fact that the geometric dimensions of a passive RF structures are in the most cases proportional to the wavelength this leads to an enlargement of the geometric dimensions. This fact especially applies to the antenna of an RF system. The trend that the RF devices have to be integrated into decreasing housings is contradictive to this. Consequently an efficient usage of the given installation space is one important aspect to overcome this challenge. 3D fabrication methods allow for selectively metalizing nearly arbitrary shaped plastic parts and thus provide the required volume efficiency. On the other hand, the operating frequencies will increase to the millimeter wave range even for consumer devices. The increasing frequency leads to a decrease of the associated wavelength that in turn increases the requirements on resolution, production accuracy and reliability of the manufacturing process. Considering the next generation of mobile telecommunication standards (5G) antennas operating at millimeter wave frequencies will presumable have to be integrated in large quantities of an increasing number of consumer devices. Therefore, the efficiency of the fabrication process by means of costs, integration spaces and functionality will be an important aspect. It should be considered that the requirements on the production process can be considerably influenced by the robustness of the RF design. The flexibility given by the fabrication process can help to optimize a device in that concern. 3D LDS fabrication is one possible method that can provide the flexibility and efficiency needed for the development and fabrication of future RF devices. Due to the fact that the LDS method is actually mainly used in applications operating below 6 GHz the frequency specific requirements for future devices have to be defined and evaluated to assure a reliable fabrication.

In the first step the main fabrication related properties influencing the RF characteristics of a device are derived (section II). Subsequently selected properties are evaluated on basis of field simulations and measurements in millimeter wave frequency range for the LDS process. The results are discussed and the main aspects that have to be considered for LDS fabrication are derived. On basis of these findings an example RF antenna operating at 24 GHz and 77 GHz is developed for verification. The main LDS fabrication parameters are specified and a RF characterization, comparing with simulated results, is done. In the last section a conclusion is drawn.

II. RF REQUIREMENTS ON MANUFACTURING

The requirements on the manufacturing method strongly depend on the specific RF structure. Therefore, in the following section there are discussed some general aspects. Subsequently, these general aspects are applied on a concrete RF millimeter wave structure that allows for a more detailed discussion.

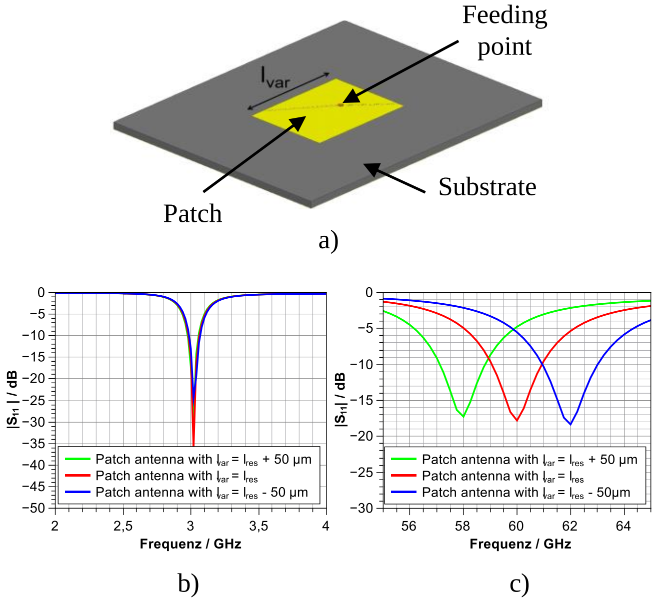

Fig. 1. Simulated input reflection coefficient for patch antenna with varied edge length l_{var}

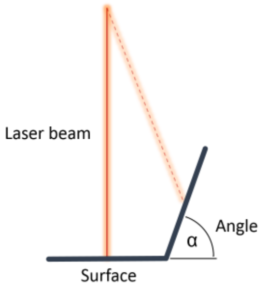

Fig. 2. Deflected LDS laser beam for the structuring and activating of 3D geometries

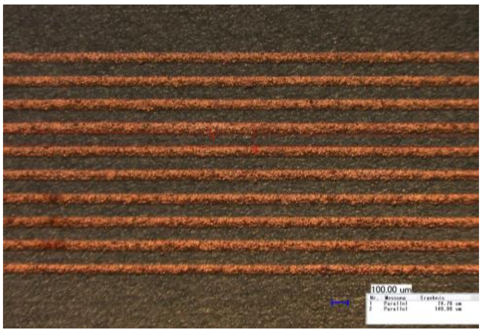

Fig. 3. LDS pattern of 75 µm / 75 µm (line/space)

Developing an RF device is typically carried out using field simulation software. The structure is built up in the software that typically provides a 3D kernel that allows using the tools that are known from typical CAD software. Besides the geometric dimensions the properties of the material building the RF structure and the surrounding boundary conditions, like for example the mixed material housing of a cell phone, have to be specified. The exact knowledge of these parameters increases the accuracy of the results that can be obtained. During the development process the RF structure is fitted by varying the geometric dimensions and observing RF characteristics like a defined input reflection coefficient or radiation pattern. In case of the 3D LDS fabrication method the structure consists out of a thermoplastic or thermoset material and a 3D metalized circuit pattern. The RF properties of the substrate material are defined by complex permittivity and permeability. An evaluation of typical LDS capable materials can be found in [2]. The properties of the metalization are mainly defined by its conductivity and the surface condition that is typically represented by the surface roughness. The metalization properties of LDS electroless plated metal sheets are discussed in the following section. Applications in millimeter wave range with its small wavelength are often geometrical fine structures. The design scope of a fabrication method and the corresponding resolution and accuracy is one important aspect influencing a RF development. As an example, Fig. 1 shows the input reflection coefficient of two patch antennas at 3 GHz and at 60 GHz. The resonating edge length l of the patch antenna is varied about 50 µm. As it can be seen from this the reflection coefficient of the antenna at 3 GHz shows nearly no change while the antenna at 60 GHz shows a shift of the resonance frequency of about 2 GHz. This is the reason why in this case the accuracy requirement for the 60 GHz antenna is higher than for the antenna operating at 3 GHz. It has to be borne in mind that the robustness of the antenna design has a high impact on the required accuracy. For an antenna with a broader operation bandwidth a slight shift due to fabrication accuracy will not influence its functionality. This is especially important for serial applications. Thus, the robustness of the antenna design can be stated as one aspect to influence the manufacturing costs. When defining the requirements for the resolution of the metalized structures (e.g. Pitch) the specific type of RF structure must be considered. As an example in [4,5] grid line and filter RF structures in millimeter wave range can be found requiring a high resolution. In contrast to this there are other structures covering millimeter wave range that have lower requirements on accuracy and resolution, e.g. in [6].

A. LDS for RF Applications

For many years now, the LDS technology has been used to manufacture mainly -though not solely- antennas for consumer devices such as smartphones, laptops and tablets. With the LDS manufacturing technology a 3D laser system transfers the RF pattern to the polymer surface of nearly arbitrary shapes and it is simultaneously activating a compounded filler (LDS additive) along the lasered areas. This activated additive serves now as a seed layer for selective cooper deposition in a subsequent electroless plating process. Copper is typically deposited at thicknesses of 5-15 µm depending on the required electrical resistance of a circuit track. Higher plating thickness deposition is generally possible but usually inefficient due to long production lead times. In comparison to solid bulk copper layers used for conventional printed circuit boards, LDS conductor tracks have significantly higher porosity and slightly lower electrical conductivity ($\sigma_{\text{electrolessCu}} \approx 0{,}6 \times \sigma_{\text{BulkCu}}$). In addition, the surface roughness of these metal layers is also higher. Contrary to electroplating processes, electroless plating does not level the surface of a metal layer even at increased layer thickness. On the other hand, plating chemicals as well as process parameters do have an influence on roughness. New copper plating technologies have been under development indicating to provide more homogenous layers and lower surface roughness. After the initial copper layer several surface finishes such as electroless nickel (EN), electroless nickel and immersion gold (ENIG), immersion silver and others can be applied to protect the copper from corrosion. Usually only a thin layer of nickel is deposited (~2-3 µm) to provide corrosion resistance while keeping cooper as the main conductor. LDS Laser tools work within a scan volume of up to 200 mm x 200 mm x 80 mm (x,y,z) and provide focused laser activation of steep areas up to $\alpha = 70°$ (Fig. 2). This maximal deflection of the laser beam allows for circuit pattern on fully three dimensional geometries and thus contributes to an increased efficiency of space utilization and functionality. LDS antennas have proven to deliver good RF performance and can be manufactured at a high level of design flexibility while keeping a short process chain. Due to current frequency ranges used for mobile antennas, the form factor requirements of RF patterns have been fairly large and dominated by a need for high productivity, therefore larger beam diameters such as 100 µm and fast laser scanners travelling up to 4000 mm/s have typically been used. The ongoing trend of miniaturization has already been driving the requirements for higher resolution of circuit tracks respectively fine pitches. Today`s LDS process technology already allows for fine patterns within the micrometer range, achieving line and space ratios down to a minimum of 75 µm/75 µm at a mass production scale. At the same time, these LDS laser systems provide an accuracy of ±25 µm within the entire calibrated scan field and take the requirements for accuracy at very high frequencies into account. As an example, Fig. 3 shows a copper plated LDS circuitry with a line and space ratio of 75µm/ 75µm. The laser slightly ablates the polymer surface and forms micro cavities providing the foundation for sufficient bonding between the substrate and the subsequent copper layer. The adhesion strength of a LDS trace is initially determined by the laser process respectively its relevant laser parameters. At the same time, this adhesion (strength) is corresponding to a specific surface roughness due to the laser ablation of these areas. Both, adhesion and surface roughness are influential by a variation of several laser and laser scanner parameters such as laser pulse energy, repetition frequency, distance of horizontal lines (hatch overlap), effective laser beam width as well as scanner speed, delay times, vector lengths, the direction of laser structuring and the inclination angle of the laser beam. All these parameters are adjustable values in order to evaluate the preferred compromise between initial adhesion strength and surface roughness. In addition, the process of electroless copper plating has an impact on both target values, hence it requests a thorough evaluation to obtain a sufficient interaction of the laser and the electroless plating process.

With the rising trend towards even thinner and smaller devices like wearables on the one hand and increasing operating frequency at the other, current specifications are expected to reach certain limitations soon. Latest development approaches have already began to open future opportunities towards smaller pitches and higher accuracy. With the help of new LDS technologies, ultra-fine pitches down to 25 µm/25 µm (line/space) will become achievable at an accuracy of ±20 µm and will provide lower initial surface roughness in order to meet future requirements of RF devices.

TABLE I. SURFACE ROUGNES OF LDS FABRICATED COPPER METALIZATION AND TYPICAL RF SUBSTRATE MATERIAL

Surface Roughness		
Material	***Sa***	***Sz***
Rogers 4003c, 17,5 µm rolled copper	1.7 µm	22.3 µm
Xantar LDS 3730, 12 µm electroless copper	6.4 µm	66.3 µm

The applied metalization of an RF device acts as boundary condition that determines the possible electromagnetic field distribution. The electrical properties, the mechanical properties and the geometrical shape have to be considered in this context. It has to be noted that these characteristics are related with each other. The condition of the metal layer induces conductor losses that occur in addition to the dielectric losses in the plastic material. The losses are determined by the electric conductivity of the plating material, the geometric dimensions and the geometric surface condition. In case of LDS metalization more than one metal layer is typically applied (e.g. Cu + ENIG). The resulting conductivity depends on the electromagnetic field distribution occurring on the specific structure. Besides this, the skin effect that defines a frequency related field displacement in electric conductors has to be considered [3].

Evaluating the condition of the surface, roughness parameters like the arithmetic mean roughness Ra or Sa and the maximum height Rz or Sz are typically used. The surface roughness values for a LDS substrate that is metalized with electroless copper and a Rogers 4003C substrate metalized with a 17.5 µm rolled copper layer are depicted in Tab. 1. The test samples were measured with Keyence One-Shot-Measurement-Macroscope VR-3000. The resulting roughness values for the LDS test samples are considerably higher. When evaluating the surface properties of the LDS metalization these higher values defined by Sz and Sa are partially insufficient due to the fact that the exact shape of the surface will additionally influence the losses. In case of the LDS manufacturing the laser causes grooves where the laser beam activated the surfaces to be metalized. This leads to a waviness that depends on the laser beam width, the overlap, the pulse repetition rate and the laser power used for structuring. Fig. 4 depicts one example of a laser structured part where the grooved surface due to the laser is analyzed. A 3D profile view of the structured (bottom) and metallized (top) surface shows the laser induced surface modulation. The plating process leads to a slight reduction of the depth of the laser induced grooves. It has to be considered that for an RF application the effective surface is not automatically the outer side of the metallized surface. Depending on the electromagnetic field distribution the inner surface connected to the substrate can also be decisive. The described surface modulation has a high impact on the resulting roughness values while the influences on the RF losses may be lower due to the

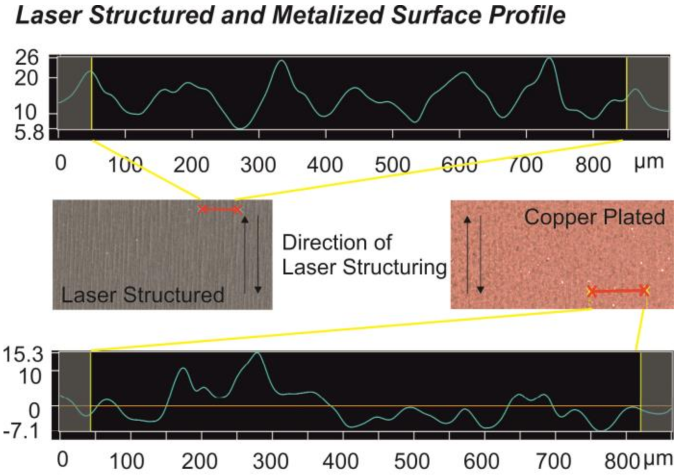

Fig. 4. Surface condition of a LDS test structure

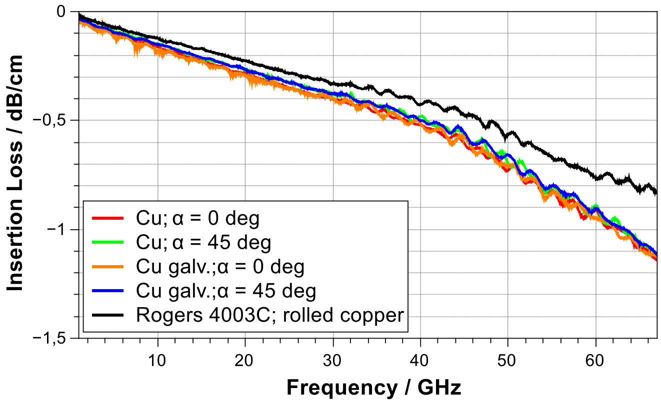

Fig. 5. Measured insertion loss for coplanar waveguide

specific shape of the surface. Therefore the RF losses are evaluated based on a field simulation where the LDS structured surface is built up as modulated surface with a sinusoidal shape. A detailed description of this investigation and the corresponding results can be found in [7]. These simulations showed that the laser induced grooves on the structured surface do not have the high impact as it may be expected. The induced losses can be influenced by the direction the part is structured. Structuring in line with the wave propagation showed nearly no differences between a smooth and a sinusoidal modulated conductor. For a structuring across the direction of wave propagation the induced losses are increased from 0.91 dB/cm up to 1.09 dB/cm for a coplanar waveguide (CPW) on Xantar LDS 3730 at 50 GHz. To prove the results evaluated by simulation in the next step the insertion loss of a CPW was measured. Different laser inclination angles ($\alpha = 0°$ and $\alpha = 45°$) are used to structure the test samples that are typical RF transmission lines, metalized with plain LDS electroless copper and galvanic reinforced copper. With the different laser angles the three dimensional fabrication process can be evaluated although a planar transmission line has to be used due to the limitations in the measurement setup. A detailed description of the measurement setup and measurements for other typical LDS metalization compounds can also be found in [7]. Fig. 5 shows the insertion loss in dB/cm for the evaluated test samples. The laser structuring is done in parallel to the direction of wave propagation with a laser angle of 45 deg and 0 deg. For comparison a CPW fabricated in a photolithographic process out of a single rolled copper layer on Rogers 4003C is measured (black line). At 60 GHz the CPW test samples with copper show a loss of about 0.9 dB/cm while the sample on Rogers 4003 with the rolled copper foil induces a loss of about 0.75 dB/cm. The conductivity of LDS copper is only about 30 MS/m while the conductivity of the rolled copper can be assumed to be above this value. Furthermore the LDS substrate material used (Xantar LDS 3730) has a loss tangent of about DF = 0.005 at 20 GHz. The Rogers 4003C laminate provides a loss tangent of about DF = 0.0027 at 10 GHz. Consequently the higher losses that can be observed for the LDS manufactured samples may not only be due to conductor losses but also due to the dielectric losses. These aspects prove the assumption that the surface roughness values of LDS copper do not have the high impact on the losses as it may be expected. This can be explained by the specific shape of the laser structured surfaces with their laser induced grooves leading to a kind of surface modulation that only slightly influences the conductor losses. Due to the fact that the coplanar samples are manufactured with different laser inclination angles ($\alpha = 0$ deg and $\alpha = 45$ deg) this applies to 3D fabricated structures. With regard to the manufacturing process the evaluations indicate that even though that there are only slight differences a structuring in parallel to the direction of the electromagnetic wave propagation is recommended.

III. MILLIMETER WAVE APPLICATIONS

As stated before in case of millimeter wave structures that should be integrated in consumer devices the costs will be one important influencing factor. Using the flexibility of the LDS fabrication can be helpful to developed robust RF designs which can be cost efficiently fabricated. Under certain circumstances millimeter wave structures may have very small dimensions due to the dependency between wavelength and geometric dimensions. While the volume efficiency aspect of 3D antenna development is more dominating for application in lower frequency ranges it will play a minor role in millimeter wave applications. Rather the flexibility, the realizable design scope, the efficient integration of required circuitry and the related fabrication costs will be a more dominant factor.

A. *Example Design: Dielectric Horn Antenna*

One example of antennas that can be efficiently used for applications in millimeter wave range are dielectric filled waveguide fed antennas. In contrast to typical air filled waveguides often realized with a rectangular or circular cross section, for a LDS manufacturable version the dielectric LDS plastic forms the waveguide together with the LDS metalization that is applied on the outer surface. Fig. 6 shows the structure of a rectangular waveguide as typically fabricated out of metal walls and the equivalent version that is manufacturable with the LDS method. An additional advantage of the LDS fabrication is that a direct combination of a circuit board and the dielectric filled waveguide is possible. For the radiating antenna element typical principles of waveguide fed structure can be used. Dielectric rods and the different kind of lens type structures as well as dielectric and dielectric coated horn antennas to only

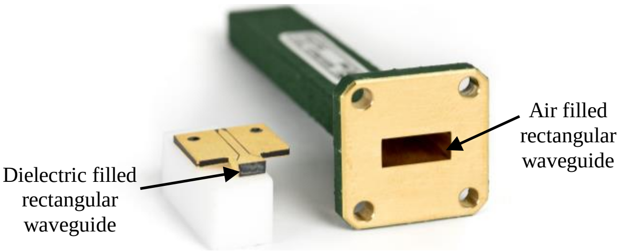

Fig. 6. Dielectric-filled LDS and typical air-filled rectangular waveguide

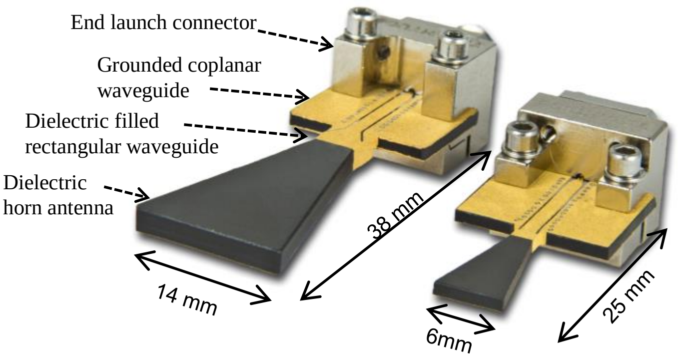

Fig. 7. Realized test structure of a dielectric horn antenna that is fed with coplanar waveguide to dielectric filled waveguide transition

name some; can be efficiently manufactured with the LDS process. The relatively simple fabrication process of such structures using the LDS method indicates the usability for future millimeter wave applications in consumer or automotive sensor applications. To evaluate the approach and the fabrication with the LDS process a test structure is developed and realized. The structure consists out of a grounded CPW that directly feeds the dielectric filled waveguide. As radiating element a dielectric horn antenna is used. The test antennas are realized covering frequencies in 24 GHz ISM Band and at 77 GHz Band that is used for automotive short range radar system. Fig. 7 shows the two realized test antennas with a description of the single components and its dimensions. The fundamental mode in the rectangular waveguide is exited using a transition from the coplanar waveguide to the short rectangular waveguide. The coplanar waveguide part represents a possible circuit part that can contain e.g. a transceiver circuitry. The antenna substrate can be manufactured with high accuracy and throughput in state-of-the-art injection molding processes. The test antennas shown here are based on 2 mm thick molded parts which are processed to final shape by milling to prove feasibility as well as to keep economical efficiency. The substrate material used is Xantar LDS 3730. The antenna plastic parts are cleaned in diluted acid before lasering in order to remove residues from the milling process. During the laser process, the parts are fixed in a turning unit which can be rotated by 360° and allow the laser head to reach every area to be structured. According to the evaluation shown in Section II, the LDS grounded coplanar waveguide as well as the dielectric filled rectangular waveguide of the antenna are structured in the direction of the electromagnetic wave propagation in order to reduce losses. The lasering is conducted on a LPKF Fusion 3D 1200 which is equipped with a 2nd Gen. processing unit and provides an average beam diameter of 100 µm. The relevant laser parameters used are depicted in Tab. 2.

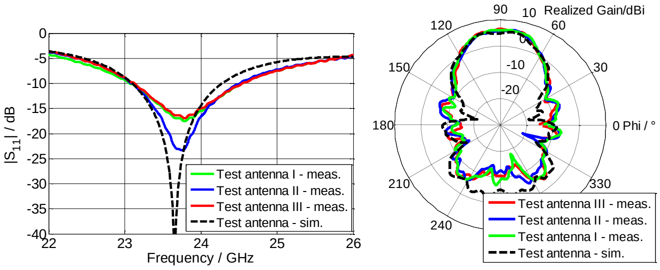

Fig. 8a. Input reflection coefficient and radiation pattern of 24 GHz dielectric horn antenna

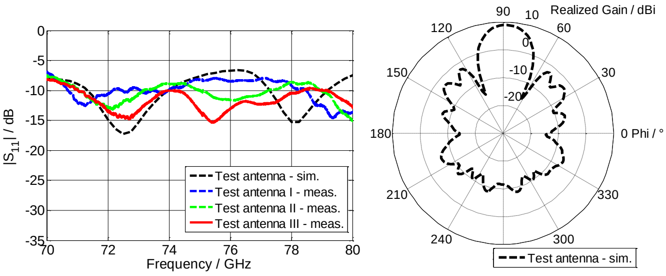

Fig. 8b. Input reflection coefficient and radiation pattern of 77 GHz dielectric horn antenna

Several evaluation runs were carried out prior to fabrication in order to determine the process window and to achieve equal surface configuration (thickness of metallization, surface roughness) for both horn antennas. The metalization thickness is measured using X-ray fluorescence (XRF) analysis. Tab. 3 shows the results.

TABLE II. LDS LASER PARAMETERS USED FOR THE DIELECTRIC HORN ANTENNA AT 24 GHZ AND 77 GHZ

LDS Laser Parameter				
Operating frequency	***Power***	***Speed***	***Pulse repetition frequency***	***Hatch Overlap***
24 GHz	5.5 W	4000 mm/s	65 kHz	50 % (50 µm)
77 GHz	6.25 W	4000 mm/s	75 kHz	50 % (50µm)

TABLE III. METALIZATION LAYER THICKNESS OF DIELECTRIC HORN ANTENNAS MEASURED BY XRF

Plating Thickness		
Cu	***Ni***	***Au***
11 µm	3,75 µm	0.15µm

Both test antennas were characterized concerning their RF properties. A detailed description of the horn antenna at 24 GHz can be found in [8]. Fig. 8 shows the measured and simulated results for the input reflection coefficient and radiation pattern at 24 GHz (Fig. 8a) and 77 GHz (Fig. 8b). There were 3 test antennas measured. It can be seen that the agreement between measurements and simulation is good for both, the radiation pattern in the main lobe direction and the input reflection coefficient. Furthermore, a good match between the three fabricated test antennas is achieved. In conclusion this indicates the reliability of the LDS technology even in millimeter wave frequency range. The main scope designing the test structures is for verification of LDS fabrication. The structures have to be

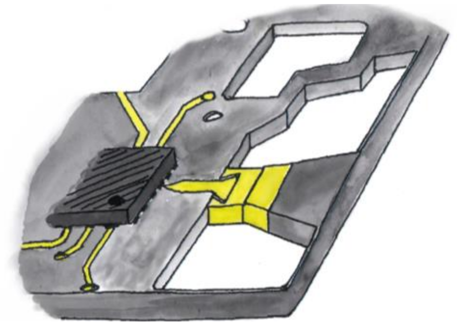

Fig. 9. Schematic sketch of a dielectric horn antenna integrated into a generic plastic part

kept relatively simple. This is the reason why the test antennas are not in an optimized state. For future application-oriented configurations the advantages of the LDS technology can for example be applied by a 3D surface impedance metalization on a 3D shaped antenna structure. In doing so, the flexibility of the 3D manufacturing can be used to develop efficient structures and face the challenges arising for future RF devices.

B. *Possible Applications for LDS Waveguide Fed Antennas*

The concept of LDS fabricated waveguide fed antennas can be used for several applications. The concept in general allows developing antennas with a broadband frequency behavior and directive radiation characteristic. This indicates certain robustness against integration effects, environmental influences and slight variations in fabrication process. Furthermore, the relatively simple fabrication using only a plastic part that is metalized on the outside leads to the assumption that the concept can be cost efficiently implemented in a series application. A possible automotive application is as a sensor antenna in radar systems for distance control and/or autonomous driving. Especially for autonomous driving a large number of sensors will be needed. The directive radiation characteristic required for these sensor antennas can be realized with waveguide fed antennas. Another possible application could be the usage in next generation mobile communication systems (5G). One way to deal with the expected increase of the network traffic is to increase the network density as it is described in [1]. This indicates that there will be a large number of short range network nodes that use operating frequencies above 10 GHz. Due to the fact that the path loss increases with operating frequency the number of these network nodes have to be increased to assure a full coverage. This in turn indicates that the costs of these devices will play a major role. With the concept of LDS fabricated dielectric, lens or horn antennas such a network node could be efficiently fabricated including the required transceiver circuitry and the devices housing. Furthermore, the concept may also be used in user devices like for example cell phones, smart wearable devices, laptops or tablets. Fig. 9 shows a schematic sketch of a possible application of the dielectric horn antenna in a generic housing of a future device.

IV. CONCLUSION

Out of the requirements that can be defined for future RF applications this article is focused on the increase of the frequency ranges up to millimeter wave range and the impact on a fabrication using 3d LDS process. First of all, the demands on manufacturing resulting out of the increasing frequencies are derived. On basis of this the LDS design scope is described for the current and future situation. In the next step these parameters are used to describe the impact on the RF properties. With a special focus on the surface roughness a coplanar waveguide fabricated with LDS method is measured to evaluate the conductor and dielectric losses. The measurements are compared to a typical RF substrate with a rolled copper layer. On basis of these measurements and additional simulations selected parameters for RF optimized LDS fabrication are discussed. In the last section a prototype of a dielectric horn antenna that is fed by a transition from grounded coplanar waveguide to dielectric filled rectangular waveguide is presented and the relevant LDS fabrication parameters are discussed. The RF characterization showed a good match between simulations and measurements. This indicates the good reliability of the LDS process for these applications in millimeter wave range up to 80 GHz.

REFERENCES

[1] E. Dahlman, S. Parkvall, D. Astély, H. Tullberg, “Advanced Antenna Solutions for 5G Wireless Access”, 48th Asilomar Conference on Signals , Systems and Computers 2014, Pacific Grove, California, USA, November 2 - 5, 2014

[2] Q. H. Dao, A. Friedrich, B. Geck, “Characterization of Electromagnetic Properties of MID Materials for High Frequency Applications up to 67 GHz”, 11th International Congress Molded Interconnect Devices 2014, Nuremberg/Fuerth, Germany, September 24-25, 2014

[3] C. H. Yen, Z. Fazarinc, R. L. Wheeler, “Timedomain skin-effect model for transient analysis of lossy transmission line”, Proc. IEEE, Vol.70, No.7, July 1982, pp.750-757

[4] Q. H. Dao, R. Braun, B. Geck, “Design and Investigation of Meshed Patch Antennas for Applications at 24 GHz”, European Microwave Conference 2015 (EuMC 2015), Paris, France, September 7 - 11, 2015

[5] Q. H. Dao, B. Lüers, T. T. Ngo and B. Geck, “An Optically Transparent Analog Frontend for a Solar Powered 24 GHz RFID Transponder”, International Microwave Symposium (IMS 2016), San Francisco, California, USA, May 22-27, 2016

[6] Z. Lin, Z. X. Wei, and Z. Y. Ping, “A microstrip grid array antenna for 24 GHz Doppler sensors”, in Proc. IEEE Asia-Pac. Conf. Antennas Propag. (APCAP), Aug. 27–29, 2012, pp. 257–258.

[7] A. Friedrich, M. Fengler, B. Geck, “LDS Molded Interconnect Devices Fit For mmWave”, Microwave Journal, vol. 59, no. 9, September 2016.

[8] A. Friedrich, B. Geck, M. Fengler, A. Fischer, “24 GHz Dielectric Filled Waveguide Fed Horn Antenna Using 3D-LDS MID Technology”, European Microwave Conference 2016 (EuMC 2016), London, UK, October 3-7, 2016