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60 GHz 3D Integrated Waveguide Fed Antennas Using Laser Direct Structuring Technology

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***Abstract*—The following contribution presents the design of waveguide fed antennas that are directly integrable into injection molded plastic parts using 3D molded interconnect devices technology. The fabrication method used for 3D metallization of the plastic parts is Laser Direct Structuring (LDS). First a single dielectric filled waveguide fed horn antenna is developed, fabricated and characterized to verify the LDS process. The results show a good match between simulated and measured data proving the principle suitability of the LDS process. Based on this the approach of integrating this type of antenna directly into plastic parts is discussed. As an example a dielectric horn antenna is integrated into a generic plastic part and evaluated based on field simulations. The antenna is developed to operate in the frequency range of the WiFi IEEE 802.11ad standard.**

***Index Terms*—millimeter wave propagation, dielectric antennas, horn antennas, manufacturing processes**

I. Introduction

For next generation of mobile communication standards (e.g. 5G, WiGig) it can be expected that this part of wireless connectivity will undergo several changes resulting in challenging requirements on the affected RF systems. One major aspect is the increase of operating frequency ranges to millimeter waves that is actually indicated [1]. In concern of the fabrication of these devices the smaller wavelength and the possibly resulting smaller geometric dimensions may increase the requirements of fabrication accuracy, resolution and reproducibility. At the same time and especially in consumer market applications the costs will be strictly limited. The exact requirements on fabrication process are mainly influenced by the type of RF structure. RF structures with a small operation bandwidth will be more sensitive for small changes in the fabrication process than a structure with a broadband behavior. Another aspect that influences the functionality of a RF device is the specific antenna characteristic. For applications in millimeter wave range a high path loss is induced. This indicates that a concept using directive antennas that provide a high gain pattern would be suitable. There can be found different concepts for future antennas in millimeter wave range using dielectric lens or horn antennas, e.g. in [2] or [3]. These types of antennas can be fed e.g. by a waveguide or a patch antenna providing typically a broad bandwidth and a directive radiation pattern. Besides the requirements resulting of the operating frequency range the integration related aspects dominantly influence the fabrication costs. Considering the fact that the housings and in that concern the provided space is decreasing the possibilities of efficient integration can be another factor to influence the fabrication costs and additionally the functionality.

Driven by those challenging requirements on electronic devices the 3D molded interconnect devices (MID) technology becomes more and more common to fabricate electronic devices including RF devices, e.g. cell phone antennas. Summarized under the term MID there are different fabrication methods, providing a slightly different design scope and mechanical as well as electrical properties. One method already proved its reliability in several series applications is the Laser Direct Structuring (LDS) technology. By metalizing nearly arbitrary shaped structures with an additive laser based method a very efficient integration with a high flexibility can be achieved. Due to the fact that the antennas can be combined with existing plastic parts a combination of mechanical and electrical function can be realized. The additional flexibility in the design scope and the fabrication process itself, can be helpful to design future RF devices and meet the challenging, often contradictive requirements.

In the following contribution the usage of the LDS method is evaluated by the example of rectangular dielectric filled waveguide fed antennas that are directly integrable in 3D injection molded plastic parts. The plastic parts investigated are generically designed to show the possibility of LDS fabrication. In case of a concrete application these parts have to be replaced by parts designed for the specific application. First of all, the LDS method is briefly described. To evaluate and verify the fabrication of the dielectric filled waveguide fed antennas with the LDS process in millimeter wave range a first prototype antenna is developed. The antenna consists of a grounded coplanar waveguide that feeds a rectangular and dielectric filled waveguide. The rectangular waveguide in turn is used to feed a dielectric horn antenna. The antenna is characterized by measurement and simulation. In the next step the concept of a direct integration of waveguide fed antennas into a given plastic part, like e.g. a housing or plastic cover, is discussed. Subsequently, an example of an integrated antenna is extracted and optimized based on simulations, operating in the 60 GHz Band (WiFi IEEE 802.11ad standard (WiGig)). In the last section the discussed topics are concluded.

Fig. 1. Different fabrication steps of the LDS process - Injection molded, structured, metalized and assembled part

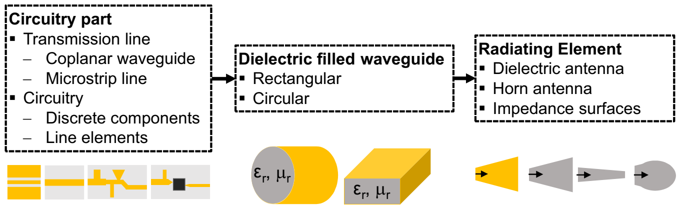


Fig. 2. Possible waveguide fed antenna configurations

II. Waveguide Fed Antennas Using LDS

For several years the LDS method has been used to fabricate, inter alia, antennas integrated in smartphones, laptops and tablets. The advantages of the 3D metallization of plastic parts provide a high flexibility in the highly integrated consumer devices. The RF systems currently integrated mainly operate in a frequency range up to 6 GHz. As already described in the last section, for future applications the advantages of the third dimension might be helpful developing millimeter wave systems. To assure a proper functionality of the LDS fabricated devices a structured investigation of the RF related charactersitics is discussed in [5]. Furthermore, a first test antenna operating at 24 GHz ISM band based on the antenna concept used in the following is discussed in [4].

A. Laser Direct Structuring Process

The typical LDS process is based on an injection molded plastic part that is doped with a mixed metal oxide and structured with a laser. The laser activates the metal oxide and causes a micro rough surface that allows for a selective deposition of copper in an electroless copper bath. Similar to conventional PCB technology, different surface finishes such as ENIG (Electroless Nickel/Immersion Gold), ENEPIG (Electroless Nickel/Electroless Palladium/Immersion Gold), Immersion Silver and others can be deposited with electroless plating processes. Alternatively, a variety of metal finishes can be applied by electroplating processes. Fig. 1 shows the different fabrication steps described. Besides several applications in DC range, the LDS method has already been used in large scale productions of antennas for smart mobile devices such as smartphones, tablets and laptops. By metalizing the surface of the housing of a device, the part count can be reduced while functionalizing an available installation space efficiently. Furthermore, the 3D design scope can be used by shaping the antenna, optimizing its characteristic like it is done by the example of a patch antenna in [6]. Other types of antennas that could be enhanced by using a 3D manufacturing method are dielectric or horn antennas that are fed by a dielectric filled waveguide. The principle concept is based on a transmission line that feeds a waveguide that in turn feds an arbitrary dielectric or dielectric metalized radiation structure. The whole antenna can be fabricated as one plastic part using typical plastic materials, e.g. polycarbonate. Fig. 2 shows possible example configurations illustrating the main principle. The LDS capable plastic parts are typically fabricated in an injection molded process, so that the shape of the dielectric antenna is only limited by the respective design rules. This allows realizing plastic parts with surface modulations like corrugated horn antennas. Additionally, the selective metallization of these dielectric surfaces can be used to influence the antenna. In that way impedance surfaces can be realized to optimize the radiation characteristic. In addition to the antenna optimization itself, the combination of circuit elements and the waveguide fed antenna can be manufactured as one part. In doing so a RF circuit can be interconnected directly to the antenna, reducing the complexity in the fabrication process.

B. Test Antenna Design

The main aim of the following test antenna development is the verification of the fabrication process for this type of antenna in the millimeter wave frequency range from 57 GHz up to 80 GHz. The antenna is not optimized for a specific application due to the fact that the design scope is limited. For the first test realization the plastic carrier had to be realized of an injection molded plate with a height of 2 mm. The outlines are cut out using a milling machine. In case of an injection molded part the full 3D design scope can be used. The design limitation for the test structure does not restrict its general purpose: the test evaluation of the LDS process for millimeter wave applications. The fabricated test antenna is shown in Fig. 3 with the single components and associated dimensions described. The test antenna design consists of a grounded coplanar waveguide that feeds a dielectric filled rectangular waveguide. The transition is done using a taper connected to the outer metal sidewalls of the rectangular waveguide. In doing so the fundamental waveguide mode H-10 is exicited. The radiation element is a dielectric horn that is tapered in only one dimension due to the aforementioned limited design scope. The dielectric horn antenna described is fabricated with LDS method, based on the LDS capable substrate material Xantar LDS 3730, a polycarbonate. The associated permittivity is ϵ_r= 3.0 and a loss tangent of $tan\delta$=0.005 measured at 3 GHz. For the following simulation the values are set to ϵ_r= 2.9 and $tan\delta$=0.007. This is done on basis of measurements of very similar types of materials in the target frequency range. The metallization is carried out with electroless copper and ENIG.

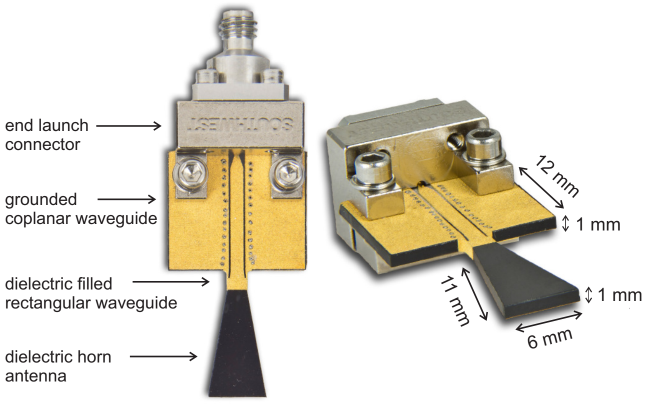


Fig. 3. LDS fabricated test antenna

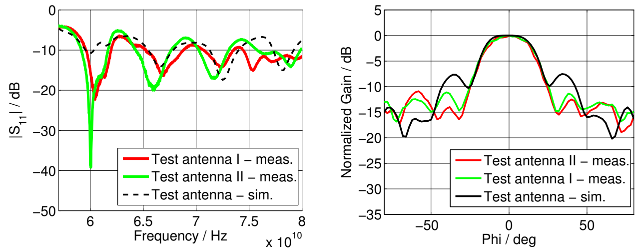
C. RF-Characterization

All simulations following are carried out using ANSYS Electronics Desktop, Version 17.0.0. The measured and simulated input reflection coefficient of the described test antenna is depicted in Fig. 4a. Two fabricated test antennas were measured. The results show an adequate match. The principle characteristic of the input reflection coefficient over frequency is verified by the measurements. The differences may result of slight differences in the permittivity that could only be calculated approximately. It even has to be considered that the measurements are carried out with the relatively large end launch connector that influences the antenna characteristic considerably. In the simulations the connector is modeled but only using a simplified model. The mechanical installation of the connector additionally influences the input reflection coefficient. Comparing the results for the two test antennas the match is adequate, indicating the reproducibility of the fabrication process for this millimeter wave application.

In the next step the radiation pattern of the antenna is measured at 75.5 GHz. The resulting normalized radiation pattern in the H-plane is depicted in comparison with the simulated results in Fig. 4b. As it can be seen from this the results show a good match for the main lobe and an adequate match for the side lobes. The match between both test antennas is also adequate indicating again the reliability of the fabrication with LDS. The measured realized peak gain for the test antenna I is $\text{gain}_{real.I} = 6.4$ dBi and for test antenna II $\text{gain}_{real.II} = 6.0$ dBi both at 75.5 GHz. The simulated results show a peak gain of $\text{gain}_{real.sim} = 7.5$ dBi. Based on the findings of the test antenna realization the possibilities of a direct integration into an injection moldable plastic part is discussed and evaluated in the following section.

III. Integrated Waveguide Fed Antennas

The results gained of the last section show the principle suitability of the LDS method to fabricate waveguide fed antennas in millimeter wave range. In case of the test antenna



(a) Input reflection

(b) Radiation pattern

Fig. 4. Measured and simulated characteristics of the test antenna

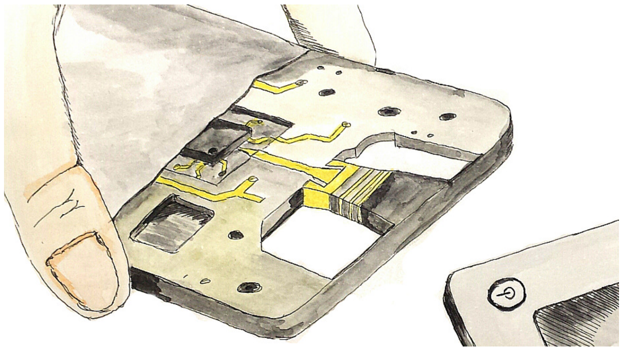


Fig. 5. Schematic sketch of future smart device containing 3D integrated waveguide fed antenna

just a limited part of the given design scope is used. Considering future RF applications the possibility gained of LDS manufacturing can be applied to integrate these waveguide fed antenna structures directly into plastic parts, combining the functionality of a mechanical (e.g. housing, plastic cover) as well as an electrical part. Another advantage of directly integrating antennas in plastic parts is that the transitions between the antenna, air and other plastic or metal parts in the housing, causing reflections and thereby also losses, can be reduced. In case of a direct integration of the antenna the electromagnetic wave can directly be radiated by or out of the plastic part. It has to be considered that this only applies to radiating structures where the main radiation takes place in the areas that are connected to the outer plastic part or housing. As an example in Fig. 5 a schematic sketch is shown depicting a possible future device with an integrated antenna and a transceiver circuitry. To reduce the height of the circuitry parts, like e.g. a packaged transceiver chip, a recess can also be designed into the plastic part like it is done in the generic sketch (Fig. 5). The required metallization for RF transmission lines and DC feeding circuitry lines are directly applied on the plastic part that additionally builds the frame of a possible plastic housing.

A. Smart Devices Antenna

In the following section a simplified model of the antenna shown in the schematic sketch in Fig. 5 is evaluated based on field simulations. The antenna development is done for an

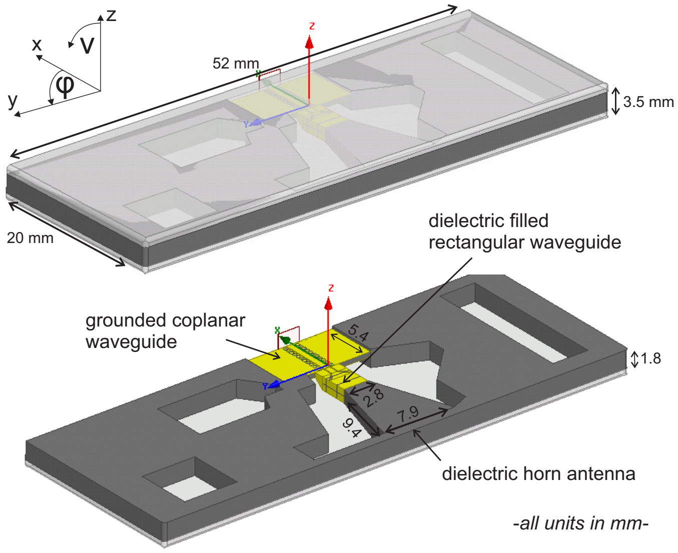


Fig. 6. Simulation model of integrated smart device antenna

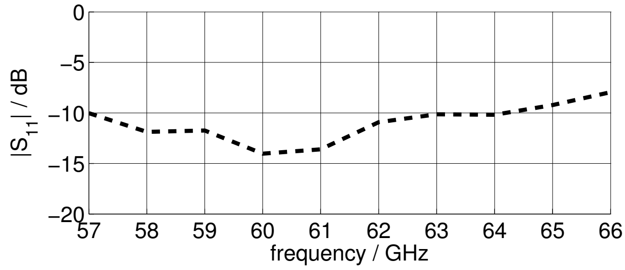


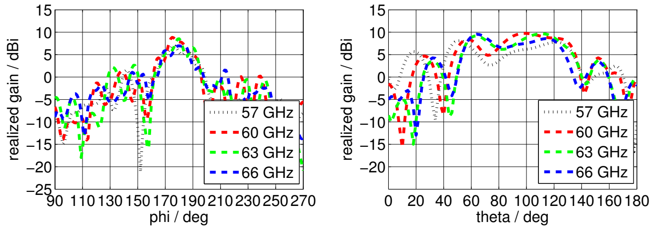
Fig. 7. Simulated input reflection of integrated waveguide fed antenna

operation frequency in IEEE WIFI 802.11ad short range data transmission (WiGig). The plastic material is set to the values used for the prototype antenna, Xantar LDS 3730. ($\epsilon_r = 2.9$, $\tan\delta = 0.007$). The respective simulation model is shown in Fig. 6. The plastic part of the integrated antenna (grey) is covered from the upper and the bottom side with plastic plates (white). So the antenna is fully integrated into the plastic part.

The simulated results for the input reflection coefficient are shown in Fig. 7. The antenna provides an input reflection coefficient below -10 dB from 57 GHz up to 64 GHz and a input reflection coefficient below -8 dB from 64 GHz up to 66 GHz. The radiation characteristics in the H- and E-plane is depicted in Fig. 8. As expected the antenna shows a directive pattern. In the H-plane the radiation characteristic shows a relativley small main lobe while in the E-plane a wider main lobe is achieved. The realized peak gain over the 60 GHz WiFi/WiGig frequency range shows a relatively smooth curvature and a maximal variation of about 2.2 dB (Fig. 9).

IV. Conclusion

In this contribution the possibilities gained of the 3D LDS fabrication method are used developing waveguide fed antennas that are directly integrable into plastic parts. In the first step a prototype antenna was designed to evaluate the fabrication process for this type of antenna in millimeter wave range. The results showed a good match for both measured test antennas in comparison with the simulations. This indicates the principle suitability of the LDS fabrication. Based on these results the possibilities that can be gained of the design scope of the LDS process for a direct integration of dielectric filled waveguide fed antennas into plastic parts are discussed. Based on this a test antenna was integrated in a generic plastic part and evaluated by simulations. The investigations give a first insight into the possibilities provided by 3D LDS fabrication for future RF antennas in millimeter wave range.



(a) H-plane (b) E-plane

Fig. 8. Simulated radiation characteristics of the integrated smart device antenna

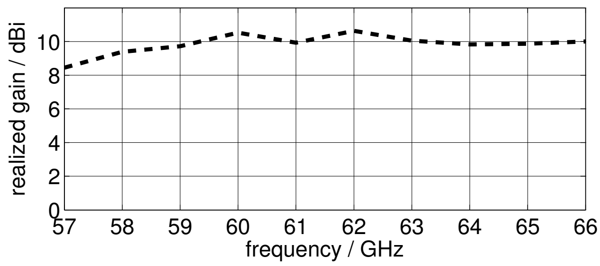


Fig. 9. Simulated realized gain over frequency

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