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An Active Three-Dimensional GPS Patch Antenna Using MID-Technology

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***Abstract*—This contribution contains the design of a three-dimensional (3d) active antenna operating in the civil global positioning satellite system (GPS) for an automotive application. Designing the antenna a new approach is used combining a slotted patch antenna with a 3d surface modulation of the antenna substrate. Thus, an optimization of the antenna dimensions is achieved considering a given installation space. In addition, the space gained due to the modulation of the antenna surface is used to integrate the circuit of a low noise amplifier (LNA). This two stage LNA designed especially for this application is positioned directly underneath the 3d surface of the antenna ensuring minimal transmission line length between feeding point and input of the LNA. A prototypical realization is done using 3d molded interconnect devices (MID) technology metalizing the 3d surface with laser direct structuring (LDS) method. The simulated and measured RF characteristics are discussed.**

Keywords - patch antenna; 3d-MID; automotive; three dimensional; active antenna; GPS

I. INTRODUCTION

Navigation and position finding with GPS is a radio service that can be found nearly in every modern vehicle. With its low signal strengths, due to the high distances to be covered in the satellite communication, the antenna system is typically designed as an active antenna combining the antenna itself with an LNA at its feed point. Besides the requirements on the functionality always further aspects have to be considered e.g. design constraints or cost and volume efficiency. Especially the design of a vehicle becomes more and more important causing in detail that the spaces for antenna integration are decreasing while the number of radio services is increasing. In terms of the production costs a reduction of complexity is one possible solution. Reducing the components of a subsystem for example may lead to the desired cost reduction. The flexibility of the production method can be named as one aspect in meeting these requirements. The 3d-MID technology allows metalizing nearly any shaped surfaces of a plastic part and is providing the high flexibility required. Especially in the cell phone industry this method is commonly used, functionalizing the plastic housing of cell phones as substrate material for antennas and RF circuits. In times of decreasing spaces this is an effective method using a given installation space. There are different methods metalizing these plastic parts [1]. One method already used for series productions of RF and non-RF applications is the LDS method. Therefore, a special plastic material doped with an organic metal complex is required. After activating the surface of the structure with a laser the activated faces are able to absorb copper in a current-free Cu bath [2]. As an alternative to a molded part with the special LDS capable plastics a varnish called LPKF ProtoPaint can be used [1]. In this way a 3d interconnect device can be realized by applying standard stereo lithographic processes. The LDS capability is achieved afterwards via varnishing. This flexible method is used to realize the prototypic active antenna system in the following.

The possibility to realize three-dimensional antenna substrates allows the design of volume efficient and functional antennas and RF circuits. Especially in applications where antennas and circuits have to be combined the 3d-MID technology ensures a reduction of complexity as both can be realized as one part. In the automotive context the flexibility of 3d-MID additionally allows the integration of radio services inconspicuously in the vehicle design [3].

II. 3D-PATCH ANTENNA DESIGN

In the following, an active antenna design for civil GPS (f_{center} = 1,575 GHz) is described. To improve the functionality a slotted patch antenna combined with a 3d modulation of the substrate surface is used. The proposed antenna is targeted to provide an input matching better than 10 dB in a 50 Ω system. A right handed circular polarization (RHCP) with an axial ratio (AR) of less than 3 dB in the upper half space should be obtained.

First of all, the slotted patch antenna is evaluated and optimized for the targeted application on a planar substrate. In the next step the patch antenna is applied on different modulated surfaces and matched again. The modulation described is done folding the whole antenna substrate including the ground plane side. Some possible configurations investigated are shown in Fig. 1. It can be seen that the 3d modulation leads to a reduction of the base area using more space in the height. The originally planar structure of the patch antenna can be optimized considering a given integration space. This ensures an optimal utilization of the available volume. As an additional advantage the resulting space under the modulated patch antenna can be used to integrate a circuit layout as it is done for the LNA in Part III.

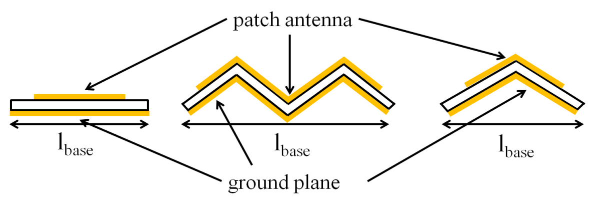

Fig. 1. Example of 3d-modulated patch antenna surfaces

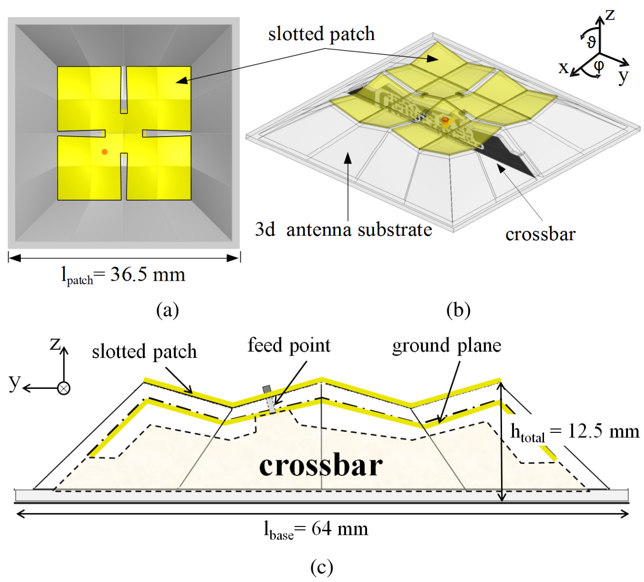

Fig. 2. 3d patch antenna part with its used description (a) top view (b) top view with crossbar (c) side view with the contour of the crossbar (------) and wall thinkness (-·-·-·-)

A. 3d Antenna Design Process

In Fig. 2(a) the slotted rectangular patch antenna is shown. The slots are used to generate the right handed circular polarization and to reduce the geometric dimensions of the antenna. The feeding is done using a coaxial feed that is positioned on the diagonal axis. Varying the position of the feed tunes the input impedance, thus matching the antenna on the input of the following LNA. Instead of straight slots like it is used in [4] the slots are widened in the middle part, lengthening the edges additionally (Fig. 2(a)).

The antenna surface is modulated under the patch surface as it can be seen in the side view (Fig. 2(c)). The different types of modulation tested (Fig. 1) showed that some of them disturb the two orthogonal patch modes in a way not to achieve the targeted AR. To ensure that the circular polarization is not disturbed, the symmetries along the x- and y-axis have to be maintained. Due to the modulation the length of the edges and the slot depth are extended on the same base area thus reducing the resonance frequency. Besides the surface modulation directly underneath the patch surface the side parts are folded down and a bit outwards (Fig. 2(c)) to obtain some extra space to integrate the LNA circuit later on. Optimizing the antenna leads to a total height of $h_{total} = 12.5$ mm and a length of the base area of $l_{base} = 64$ mm. The length of the modulated patch is $l_{patch} = 36.5$ mm and the height due to patch modulation is $h_{patch} = 3$ mm. The resulting space under the antenna is used to install a small crossbar on which the circuit elements can be placed on. This crossbar is fixed only at three points not to interrupt the metallization of the ground plane underneath the patch face with the main surface current distribution. The antenna`s functionality is only slightly influenced by this procedure. One fixed point in the middle of the crossbar is used to root the feeding point of the antenna to the input of the following LNA circuit as depicted in Fig. 2(c).

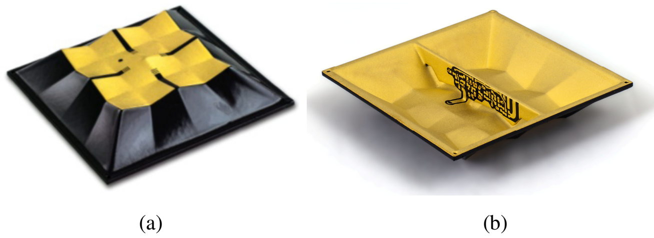

Fig. 3. Realized prototype antenna (a) top-view (b) bottom view

B. Simulated and Measured Results

In this section the measured as well as the simulated results of the prototypic realized active antenna, depicted in Fig. 3, are discussed. All simulations are done using Ansys HFSS 14.0.1. The relative permittivity of the epoxy resin used is $\varepsilon_r = 3.4$ and the loss tangent tan $\delta = 0.018$, both measured at 1 GHz. Since the permittivity value of this material is lower than substrate materials typically used for GPS patch antennas it is obvious that the dimensions of the antenna will increase. The realized gain may be reduced due to the dielectric losses. However, this does not matter in this prototyping application. In a later series production a LDS material could be used for the molded part. There are LDS capable materials available with comparable properties to that of materials typically used for RF applications [5]. Moreover, the permittivity changes due to the LDS varnishing of the epoxy resin part have to be considered during the simulations. For this reason, the permittivity value was set to $\varepsilon_r = 3.29$ for all simulations.

For the measurements and the corresponding simulations in the following the prototype antenna (Fig. 2) is contacted with an SMA connector for circuit board installation at the feed point and placed onto an aluminium plate of $250 \times 250 \times 3$ mm. Fig. 4(a) shows the simulated and measured return loss of the antenna. In the targeted frequency range an input matching better than 10 dB is obtained, marked with a line. The resonance frequency measured and simulated differs about 25 MHz. This may be caused by differences in the resulting permittivity of the LDS varnished epoxy resin. The evaluation of the radiation characteristics is done at the respective resonance frequency. Fig. 4(b) shows that the AR is minimal at resonance frequency for both, the measured and the simulated values. An AR of 1.5 dB is obtained in simulations and 2.8 dB for the measured structure. Fig. 4(c) shows that the maximum value of the AR is less than 6 dB (simulated) and less than 8 dB (measured) for nearly the whole upper half space where incident signals can be expected. The radiation characteristics in Fig. 4(d) show a good agreement between the measured and simulated results. The maximum antenna gain is about -2.5 dBi at the zenith.

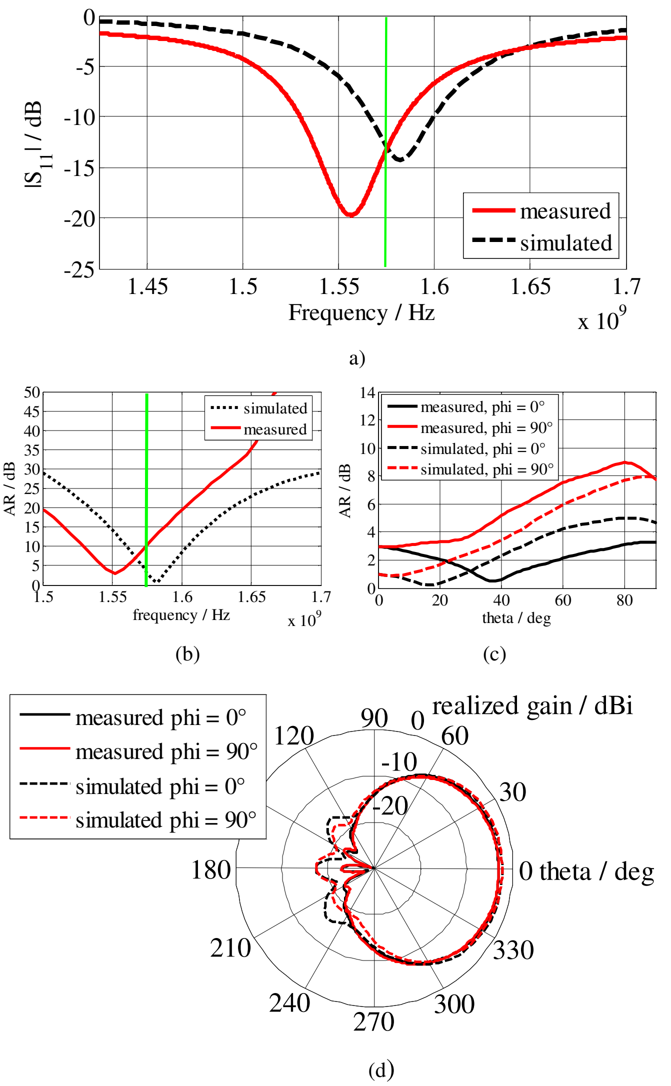

Fig. 4. Simulated (----) and measured (———) values of the 3d patch. (a) reflexion coefficient (b) AR versus frequency (c) AR versus ϑ and (d) radiation pattern

III. Low Noise Amplifier

The 3d antenna design shown in the last section allows the integration of circuit components like an LNA or matching network close to the feeding point. For an active antenna the integration of the LNA close to the feeding point is of particular importance for the reduction of the system noise figure. Another aspect illustrating the advantages of the 3d antenna design described here is that the ground plane of the patch antenna additionally shields the circuit on the crossbar against electromagnetic interferences. The low signal strengths in GPS applications show the importance of this fact.

For the design of the LNA a two-stage approach is used. As the first part of a RF system influences the noise figure of the overall system the most, the first amplifier stage is designed minimizing the noise figure. After this first stage a surface acoustic wave (SAW) filter EPCOS SAW RF filter B3522 [6] follows. The second amplifier stage does not need to be as low noise as the first stage. Thus, other

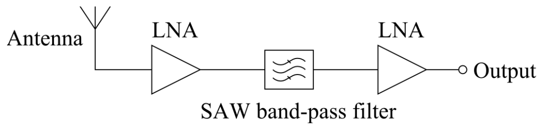

Fig. 5. Block diagramm of the designed two-stage LNA.

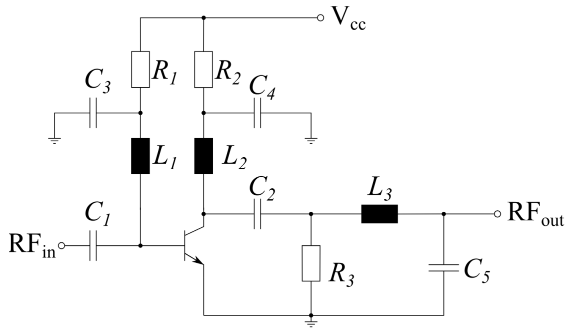

Fig. 6. Schematic of the designed first amplifier stage.

aspects can be considered as design goal depending on the specific application. Fig. 5 shows the block diagram of the amplifier design. The supply voltage is set to be provided as 3.3 V phantom powering.

For the layout of the LNA circuit the integration space has to be considered. This means in detail that the circuit design has to fit on the crossbar and has to be realizable with the LDS ProtoPaint method. The backside of the crossbar is metalized and connected to the patch antenna ground. Thus, the patch antenna and the LNA circuit have the same ground reference.

A. Amplifier Design

As mentioned before, the design goal for the first stage LNA is minimizing the noise figure. Furthermore, a small bandwidth should ensure the rejection of unwanted signals especially in the cell phone communication frequency range. With regards to these specifications the amplifier design is done using noise matching instead of impedance matching. Fig. 6 shows the schematic of the designed first stage LNA. It is a class A amplifier based on the transistor BFP640FESD from Infineon and a reference design of the manufacturer [7]. The operating point set via the resistors R_1 and R_2 is optimized for a minimum noise figure, which is mainly influenced by the collector current. To ensure that the biasing is independent from the RF part of the circuit, two coupling capacitors (C_1, C_2) are integrated, disconnecting the DC voltage from the rest of the circuit. These capacitors are also used to reduce the complexity of the matching network in the next step. Input noise matching is realized with C_1 and an inductive element L_1 connected to ground via a large capacitor C_3. The capacitor C_3 is a short for RF signals and additionally prevents the noise matching from being influenced by the biasing resistors. The DC supply is provided via L_1. To achieve an better frequency selectivity the transistor is loaded with a series resonant circuit that is connected to the collector of the transistor (L_2, C_4). The bias resistor R_2 has an attenuating effect. Close to the resonance of the LC circuit it is a short to ground causing a reduction of the amplification. With this technique a frequency range can be excluded from the amplification and selectivity

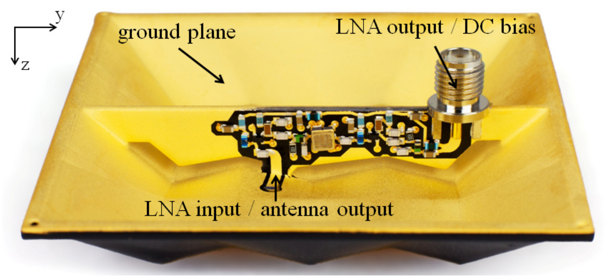

Fig. 7. Realized antenna prototype with LNA layout integrated on crossbar

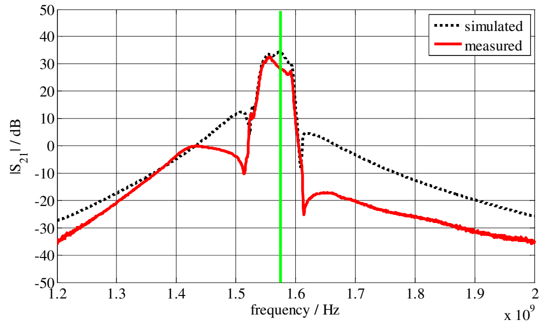

Fig. 8. Simulated and measured transmission coefficient of the LNA

can be achieved. To ensure the stability of the circuit an additional resistor R_3 is connected in series with the coupling capacitor C_2, parallel to the output. These elements reduce the amplification for lower frequencies additionally. The last step is matching the output for power transmission. Therefore an LC series circuit is used, acting as an additional low-pass filter (C_5, L_3).

All simulations shown in the following are performed with Keysight Advanced Design System (ADS), version 2013.06. The simulated values for this first stage LNA indicate a noise figure of $F_{\text{Noise}} = 0.76$ dB and a gain of $G_{\text{LNA}} = 17$ dB. The second stage of the amplifier is a commercial SAW filter for GPS applications. It improves the selectivity of the amplifier. For the second LNA stage the same design as for the first stage is used.

B. RF Characterization

In the following the measured and simulated RF properties of the two stages LNA as described in the previous section are discussed. The layout of the two stage amplifier considers the space resulting on the crossbar underneath the 3d patch antenna out of section II. Fig. 7 shows the realized LNA circuit integrated on the crossbar of the prototype antenna. For the measurements a SMA connector is used on the output side. The power supply is done via bias tee. On the input side a semi rigid line is used to contact the LNA at the feeding point of the antenna, without the antenna connected.

Fig. 8 shows the magnitude of the transmission coefficient. The gain in the desired frequency range, marked with the line, is about 36 dB (simulated) and 28.3 dB (measured). The differences may be caused by component tolerances. Furthermore, the measured results show a higher out of band rejection. Referred to the carrier the attenuation at the cell phone communication frequencies is about 73 dB at 827.5 MHz and 55 dB at 1885 MHz.

The 1dB compression point is about $P_{1\text{dB,IN}} = 19.9$ dBm. This value is comparable to other GPS amplifiers. The measured In-Band IIP_3 is $IIP_3 = -5{,}1$ dBm for the input signals $f_1 = 1.574$ GHz und $f_2 = 1.576$ GHz with an input power of $P_{\text{in}} = -35$ dBm. A comparison of these results with those of an automotive compliant commercial LNA for GPS [8] shows that the designed LNA provides comparable characteristics. In addition the circuit design is fully integrated under the 3d patch antenna and realizable with the 3d LDS method.

IV. Conclusion

In this contribution an active patch antenna design was shown and discussed. As a new feature the surface of the patch antenna was modulated and folded reducing the base area of the antenna while spending some extra space in the height. The resulting space under the antenna was used for the integration of an LNA circuit. A prototype was realized in a stereo lithographic process and the metallization was done using LPKF ProtoPaint. The presented LNA is compatible to be integrated under the antenna surface and meets the requirements for a GPS LNA. All in all the discussed active antenna is a good example, showing the possibilities of the 3d MID technology to enhance antenna and circuit design for the future demands on radio systems, especially for automotive applications.

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