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Telemetric angle sensing using additively manufactured millimeter-wave metamaterial

Alexander Schossmann[1], Michael Töfferl[1], Christoph Schmidt[1], Christof Michenthaler[2], Dirk Hammerschmidt[2], Alexander Bergmann[1]
[1] Institute of Electrical Measurement and Sensor Systems, Graz University of Technology, Austria
[2]Infineon Technologies Austria AG, Villach, Austria
alexander.schossmann@tugraz.at

Summary:
We present a fully telemetric sensor concept for real-time end-of-shaft angle measurement. It is based on additively manufactured metamaterial consisting of out-of-plane oriented structures. The sensor effect is based on the angle-dependent coupling of linearly polarized electromagnetic waves into the fundamental resonance of the metamaterial. This allows to quantify the rotation angle as a function of the reflection amplitude.

Keywords: Angle measurement, metamaterial, millimeter-wave, telemetric sensor, end-of-shaft measurement

Introduction

Angle sensors are widely used in automotive and robotics applications [1]. Most sensor systems are based on the fundamental idea of sensing the change in the magnetic field, either through CMOS-scaled magnetic sensors [2] or Hall effect sensors [3]. Encoders based on sensing the magnetic field have proven to be reliable transducers, but still have relevant drawbacks. On the one hand the measuring distance between the shaft end and the sensor is limited to *1-3 mm* [3], on the other hand they are sensitive to interfering electromagnetic fields. We propose a fully telemetric approach to angle measurement using additive manufactured millimeter-wave metamaterial, insensitive to electromagnetic fields outside the bandwidth of the metamaterial resonance.

Sensor concept

Our sensor concept is based on the fundamental resonance of Electric-LC resonator (ELC) metamaterials [4]. The coupling to this fundamental resonance depends on their orientation to the electric field polarization. Based on that, the idea is to irradiate an ELC-array with linearly polarized millimeter-waves and trace the reflection signal as a function of the rotation angle. We used additive manufacturing (Nano Dimensions) to produce the metamaterial target as shown in Fig. 1 and Fig. 2. The ELC elements are printed using nanometric conductive ink (AgCite™ 90072 Silver) in a square lattice arrangement embedded in a circular disc of dielectric (DragonFly LDM 1092). This allows a high density of structures in the metamaterial. The bottom of the disc comprises a solid conductive layer using the same conductive ink.

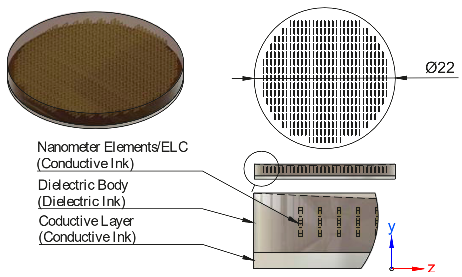

Fig. 1 Dimensions of the metamaterial (in mm)

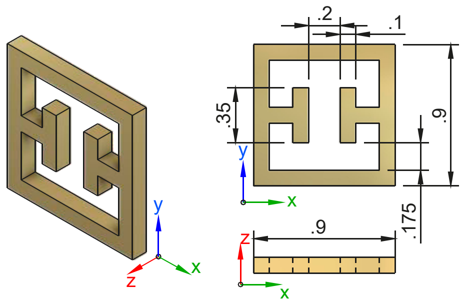

Fig. 2 Dimensions of the metamaterial elements (ELC) in mm

The geometrical parameters of the unit cell for a desired resonance at about $60\ \mathrm{GHz}$ were obtained from finite element simulations (COMSOL Multiphysics®). The linearly polarized millimeter-waves propagate along the *y*-direction. The coupling to the fundamental mode is maximized when the *E*-field is parallel to the *x*-direction.

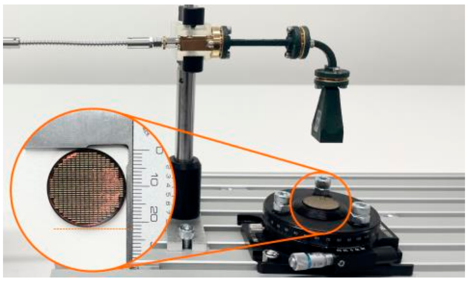

Fig. 3 The metamaterial mounted on a rotatable base plate.

Experimental results

We performed free-space measurements of the *S11* parameters using an *Anritsu MS4647B* vector network analyzer (VNA) with an external millimeter-wave test set and a *WR12* horn antenna. We conducted a calibration at the waveguide bend without the antenna. Thus, gating the data in time-domain in the postprocessing step was required. The metamaterial sample was mounted on a precision rotational stage (*Thorlabs PR01/M)* using a 3D printed adapter made from polylactide (PLA). The *S11*-spectra were recorded for various rotation angles and different distanced *d*. Fig. 4 illustrates the *S11*-spectra for a distance of $d = 38$ mm between antenna and metamaterial sample. For a rotation of $90°$ the data shows a distinct minimum at about 78 GHz which arises from the characteristic resonant behavior of the metamaterial. The deviation from the simulated 60 GHz are most probably caused by manufacturing imperfections.

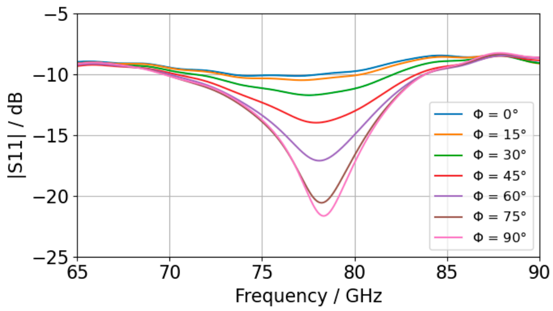

Fig. 4: VNA measurement of metamaterial, S11 spectra for different rotation angles, antenna distance d = 38 mm.

As expected, the data shows a decreasing minimum for increasing angles between the polarization of the *E*-field and the spatial orientation of the metamaterial. To check that this effect is independent of the measurement distance, we performed a measurement for three different distances between antenna and metamaterial (Tab. 1). From each obtained spectrum we evaluated the resonance minima in dB as a function of the rotation angle. Results are shown in Fig. 5.

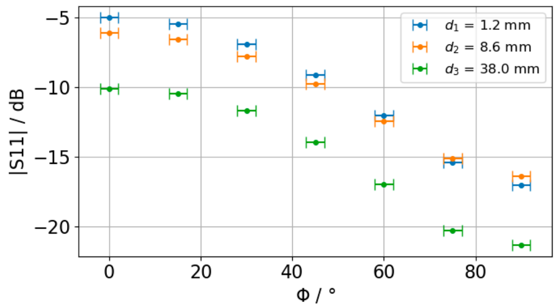

Fig. 5: Minima of measured S11 amplitude spectra as function of rotation angle.

The data shows the expected sensor effect for all three measurement distances: The reflection amplitude at the resonance frequency is changing as a function of the rotation angle. The curves only differ in an overall *S11*-amplitude offset. With larger distances, more surrounding objects are irradiated which leads to reflections that overlap with the reflections originating from the metamaterial. In order to assess the performance at different distances we quantified the observed minima by calculating the Q-factor at $\Phi = 90°$, using a Lorentzian fit.

Tab. 1: Q-factor for the measured distances

Distance/mm	1.2	8.6	38.0
Q-factor	11.6	11.0	9.8

Tab. 1 shows that the Q-factor only marginally decreases when the measurement distance is increased to $d = 38$ mm. Thus, our proposed sensor concept is suitable for a broad range of distances. Further work comprises the implementation of millimeter-wave chip technology for a compact sensor system.

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