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Telemetric angle and position sensing using millimeter-wave metamaterial and a FMCW chip

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Summary:
A fully telemetric sensor concept is presented for real-time angle and position measurement using millimeter-wave metamaterials that exhibit Fano resonant behavior. The idea is to determine the angle of rotation from the reflection signals of a millimeter-wave transceiver chip. A metamaterial geometry exhibiting Fano resonance behavior has been designed and implemented on low-cost FR4 laminates. In addition, we show numerical and experimental analysis of the sensing effect and present the implementation with a frequency-modulated continuous wave (FMCW) chip.

Keywords: Angle measurement, position measurement, telemetric sensor, metamaterial, millimeter-wave

Introduction

Real-time position measurement, rotary as well as linear, is a fundamental quantity in powertrains and robotics. In this context, there is also a high demand for telemetric and contactless position sensors [1,2].

Sensor concept

It has been shown that planar metamaterials can exhibit Fano-type resonances that significantly determine their reflectivity [3]. The basic idea of our sensor concept is to exploit these Fano resonances which, due to their anisotropy, strongly depend on the orientation of the unit cell with respect to the polarization of the electric field. This results in an angle-dependent reflection of the metamaterial target, which can be used to determine the angle of rotation.

Numerical analysis

The metamaterial used in this work has a unit cell structure as shown in Fig. 1a. The metamaterial elements were fabricated on Panasonic R-1755M laminates with a thickness of 1.2 mm using standard PCB technology. We performed finite element simulations (FEM) in COMSOL Multiphysics®, extrapolating the material parameters of the laminate to the millimeter-wave range. The geometrical parameters were optimized to set the resonance frequency of the Fano type in the frequency range of the FMCW chip, which ranges from 58.0 GHz to 63.5 GHz.

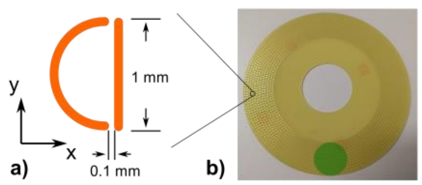

Fig. 1. Metamaterial. a: Sketch of unit cell. b: Array on FR4 disc. The dotted circle marks the illuminated area.

We simulated S11 amplitude spectra for various angles ϕ between the electric field polarization and the x-axis in Fig 1a. Results are shown in Fig 2 for ϕ in the range between $0°$ and $90°$.

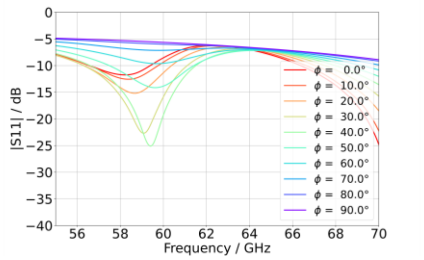

Fig. 2. Simulation of metamaterial S11 spectra.

Due to the symmetry of the unit cell, the curves in the range from $90°$ to $180°$ overlap with those from $0°$ to $90°$. The curve for $\phi = 40°$ shows a distinct minimum close to $60\,\mathrm{GHz}$ which comes

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from the Fano-type resonance. Thus, the coupling to this mode is maximum for $\phi = 40°$. Most importantly, the data shows that varying ϕ significantly changes the reflectance in the frequency range close to the Fano resonance, which in turn allows to determine the rotation angle by measuring the reflectance.

VNA measurement results

The metamaterial is produced as a single layer on a 10 cm diameter disc in a circular arrangement (see Fig. 1b). All unit cells are aligned parallel to each other. The disk is mounted on an aluminum axis together with a degree disk for reading the angle of rotation. Reflectance measurements were performed using an Anritsu MS4647B vector network analyzer and a horn antenna. The measurement distance to the metamaterial was 1 cm. The area of the metamaterial array irradiated with this setup is outlined as a green circle in Fig. 1b. In a post-processing step, we performed time domain gating. Fig. 3 shows the measurement results.

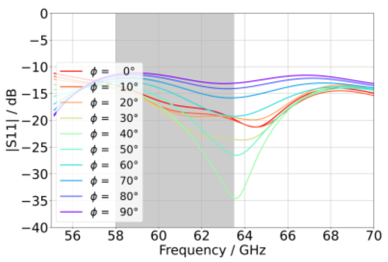

Fig. 3. VNA measurement of metamaterial S11 spectra. Grey area: Bandwidth of FMCW chip.

There is an overall horizontal shift of the curves compared to the simulation results (Fig 2). This indicates that the dielectric constant of the laminate is smaller than the value we extrapolated. In the range from $40°$ to $90°$ the change of the curves with increasing ϕ agrees well with the simulated ones. Furthermore, the coupling to the Fano-type resonance is maximum at $40°$. For ϕ between $0°$ and $30°$ the data in Fig 3 shows a shift of the minimum towards higher frequencies whereas the simulated curves show a shift towards lower frequencies. We explain this by the fact that in the FEM simulations plane wave incidence was assumed. Due to the small measurement distance, this is not strictly fulfilled in the experiment, which leads to a different coupling behavior for small values of ϕ. Nevertheless, the measured curves show the proposed sensor behavior for frequencies in the FMCW chip bandwidth (grey in Fig 3).

FMCW chip measurement results

We installed the FMCW chip at 3 cm distance to the metamaterial, considering the FMCW chirp bandwidth of 5.5 GHz. We calculated the amplitude spectra using the on-chip FFT routine and identified the peak that corresponds to the reflection from the metamaterial. Fig 4 shows the measured amplitude as a function of ϕ.

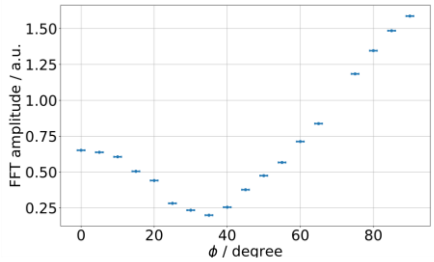

Fig. 4. Millimeter-wave transceiver: FFT amplitude as function of the rotation angle ϕ.

The horizontal error bars show the estimated reading error of the setup. The data clearly shows the angle-dependent change in the reflectance of the metamaterial. However, the curve in Fig 4 is not a bijective function over the whole range of ϕ. This is explained by the resonant behavior observed in simulations as well as measurements (Fig 2 and Fig 3) which show that the coupling to the Fano-type resonance is maximum at $\phi = 40°$. Our implementation can measure the rotation angle fully telemetric in the range from $40°$ to $90°$. However, the implementation of a sine encoder would be straightforward by varying the orientation of the unit cells in the metamaterial array such that the reflectance changes sinusoidally as a function of the sample's rotation angle or movement as sketched in Fig 5.

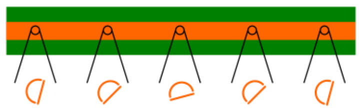

Fig. 5. Possible implementation of sine encoder

We are confident that our proposed sensor concept potentially paves the way toward a new angle and position sensor technology based on millimeter-wave metamaterials.

References

[1] S.R. Ruocco, Robot sensors and transducers, *Open University Press Robotics Series,* ISBN: 978-94-011-6870-0

[2] D. Nyce, Linear position sensors: theory and application. *John Wiley & Sons.,* ISBN: 978-0-471-23326-8

[3] V. Fedotov, M.Rose, S. Prosvirnin, et al., Sharp Trapped-Mode Resonances in Planar Metamaterials with a Broken Structural Symmetry, *Physical Review Letters, 99, 14 2007,* doi: 10.1103/PhysRevLett.99.147401