SLOT ANTENNAS AND QUASIOPTICAL BEAMFORMING FOR A COST-EFFICIENT INTEGRATED AUTOMOTIVE RADAR

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SUMMARY

A substrate lens concept has been evaluated as possible design solution for low-cost automotive radar. Slot antennas with coplanar feed integrated on a quartz substrate are employed as radiators. Antenna slots are designed to operate at the first resonance to reduce their size and increase input impedance. Input reflection bandwidth (VSWR=2:1) of the slots is 2GHz centered at 24GHz. The lens is made of plastic material with dielectric constant equal to that of quartz to avoid excitation of surface waves. A 5-element array of slots has been designed to demonstrate discrete beam scanning in the lens system. Beamwidth of around 10º and deflection pitch of 8-12º have been measured. The measured values are in good agreement with theoretical predictions.

INTRODUCTION

Automotive radar systems are currently leaving research labs and becoming consumer products. Today radar equipment is offered only in high-end car models, however it is anticipated that automotive radar will soon become much more widespread. While in the last couple of years radar sensors have been employed mainly for intelligent cruise controls, the focus nowadays is shifting to active safety systems, where a network of short-range radar sensors should monitor immediate surroundings of a vehicle for collision avoidance by issuing a warning or by an automatic intervention. To make such systems affordable for a regular customer it is necessary to identify and develop fabrication technology suitable for circuits operating at 24 or 77GHz and inexpensive in volume production. Not only manufacturing cost of microwave boards or substrates should be sufficiently low, but the number of required semiconductor components should be minimized.

The concept of quasioptical beamforming by means of a substrate-lens antenna has been known for quite a while and extensively explored with focus on applications in radio astronomy and remote sensing at 100-1500GHz; see, for example [1][2][3] and references therein. Recently attempts have been made to apply the substrate lens technique for wireless communications at 30GHz [4]. Our work is concentrated on adapting substrate lens antennas for automotive radar devices operating at 24GHz.

The most obvious advantages of a substrate lens at mm-wave frequencies are 1) increase of effective aperture of a single planar radiating element (patch, dipole or slot) from several mm^2 to several cm^2, and 2) elimination of risk for surface waves which are otherwise likely to get excited by an antenna element on a planar substrate. An additional advantage, especially pointed out in [4] and [5], is that a substrate lens antenna allows for a very simple and inexpensive method of beam deflection. Beam steering is performed by placing several radiating elements (patches or slots) at different offsets from the lens axis and switching them in one at a time (Figure 1). This scheme requires essentially only one tranceiver channel and one or two SPnT switches, which results in a drastic reduction of number of required active components as compared to electronically steered phase arrays, where each antenna patch requires a phase shifter and an amplifier.

To realize the radar circuit with integrated radiating elements we have used multi-chip modules manufactured using thin-film technology (MCM-D) which gives an appropriate patterning precision. In this paper we present our design considerations and measurement results for the first set of test substrates with integrated antenna slots.

SUBSTRATE LENS AND SLOT ANTENNAS

The optimum shape of a lens is calculated using geometrical optics. For aperture sizes $a<100\lambda$ geometrical optics is not exactly valid, however for this kind of calculations it remains a very good approximation. The resulting shape is an extended ellipsoidal lens [4]. Expressions giving the lens shape and its schematic drawing are presented in the Figure 1, right panel.

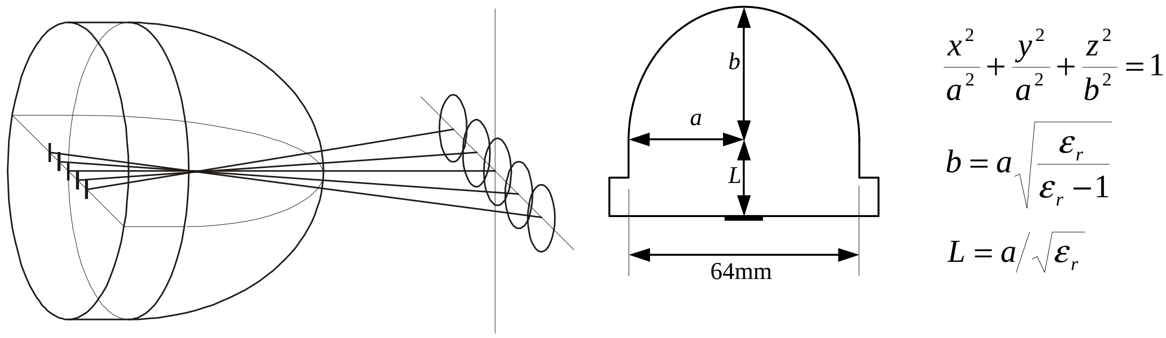

Figure 1 Beam deflection using a substrate lens (left) and lens shape drawing (right).

We use quartz (ε_r = 3.8) as substrate material for the antenna module and a low-loss plastic material with the same dielectric constant for the lens. The resulting lens dimensions are a = 32.00mm, b = 37.28mm, and L = 16.42mm. The theoretical directivity for this lens is D = 23.8dB and the -3dB beamwidth is 11.9° [8].

For discrete beam steering it is desirable to distribute radiating elements in an array so that the lobes will overlap at -3dB power level. An appropriate displacement can be calculated knowing the nominal width of a lobe. In our design we position five elements in a row with placement pitch d = 5mm resulting in the angular deflection pitch of 9.5°.

We have chosen to use a coplanar-fed slot antenna as radiating element. One reason for this is that the whole module design is coplanar in order to enable mounting of components on the substrate side not facing the lens and to reduce module cost by employing a single-layer manufacturing process. The other reason is that slot antennas usually have much wider bandwidth compared to microstrip patch antennas. The latter fact has to do with a design contradiction in the patch antenna optimization – to maximize bandwidth one should use a thick dielectric layer, but this results in easier excitation of unwanted surface modes in the dielectric [6]. Bandwidths (VSWR=2:1) up to 20% can be relatively easily reached for a simple slot antenna, while for a microstrip patch it is somewhat of a design challenge.

The most classical slot antenna design is based on slots excited at their second resonance [7], where magnetic current has zero in the feeding point (as well as at the ends of a slot),

$$I_m = I_{\max}\sin\left(2\pi\frac{l-x}{\lambda_{eff}}\right),\quad 2l \approx \lambda_{\text{eff}} \text{ (total slot length)}$$

Total slot length in this configuration is close to λ_{eff} (7.5mm at 24GHz for a quartz substrate). Resulting slot impedance is usually below 50Ω, however match to a 50Ω-feed can be achieved by employing a quarter-wave transformer. In our case a second-resonance slot could not be used partly because of its size ($2l > d$), partly because the low-impedance co-planar waveguide (CPW) needed for the transformer would require extremely narrow side gaps.

Our solution to both impedance problem and element size problem is to use slots excited at the first resonance, i.e. with magnetic current having maximum in the feeding point,

$$I_m = I_{\max}\cos\left(\pi\frac{x}{l}\right),\quad 2l \approx 1/2\,\lambda_{\text{eff}}\,.$$

In this case the total slot width is only about $\lambda_{eff}/2$ (<4mm) and slot impedance is close to 260Ω. Thus a slot can be matched to a 50Ω-feed with a high-impedance quarter-wave transformer, which can be readily realized in our substrate technology.

MEASUREMENT RESULTS

Measurements on antennas have been performed with HP8510C network analyzer. Reflection and coupling measurements have been done by on-wafer probing; antenna pattern measurements have been made in an anechoic chamber at several spot frequencies. Figure 2 (left panel) shows measured and simulated reflection coefficient for two adjacent slots (S11, S22) and measured coupling between these slots. A good correspondence between measured and simulated curves can be seen, though a 1-2dB degradation is present (the resulting VSWR=2:1 bandwidth is 2GHz instead of predicted 3.5GHz). Coupling between the slots is -17.6dB at 24GHz.

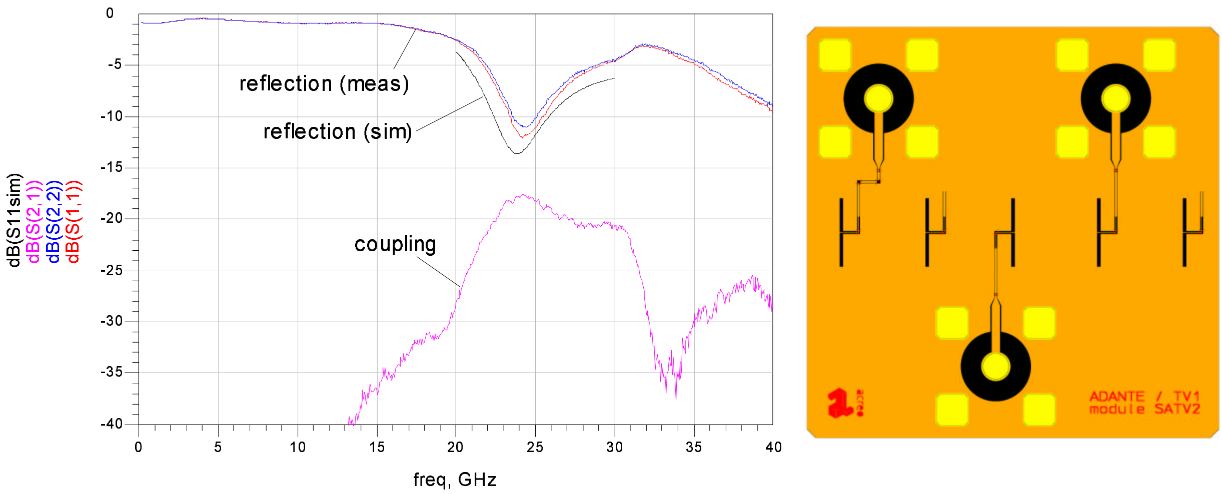

Figure 2 Left panel: return loss from the antenna slots (S11, S22 measured and simulated) and coupling between adjacent slots. Right panel: layout of the slot array; three of five slots have connections to surface-mounted SMA connectors.

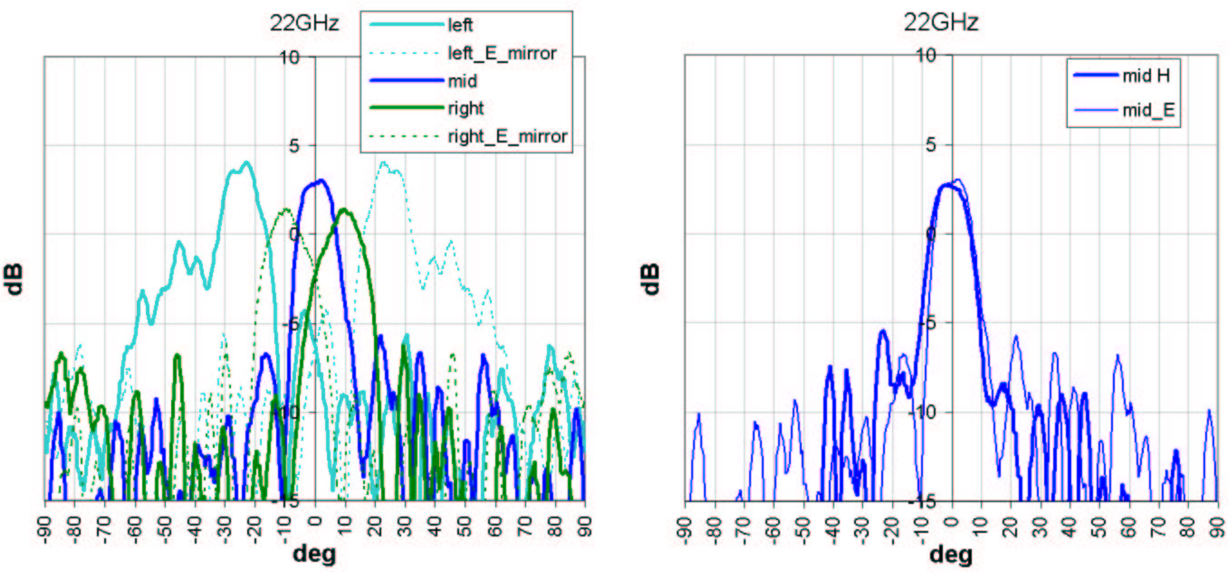

Figure 3 Radiation patterns of slots on the backside of the substrate lens antenna. Left panel shows E-plane patterns for three different slots furnished with SMA connectors (dashed lines are mirrored curves added to give a visual impression of beam overlapping). Right panel compares E-plane pattern and H-plane pattern for the middle slot. Measured at 22GHz.

Figure 3 shows results from antenna pattern measurements. The module layout is displayed in the Figure 2, right panel. Absolute level of transmitted power is affected by mismatch between CPW feed lines and hand-soldered SMA connectors. Hand soldering is also the most probable reason of level variations between different slots. On the left panel of Figure 3 one can see beam deflection performed by connecting slots with different offsets from the middle of the substrate to the feeding coax cable. Both beamwidth (about 10°) and deflection pitch (8-12°) correspond quite well to the theoretical values (11.9° for the beamwidth and 9.5° for the pitch). On the left panel pattern in the E-plane (along the array) and in the H-plane (perpendicular to the array) are shown for the middle slot. Since only E-plane pattern can be affected by proximity of other slots, similarity of the two curves on this graph demonstrates that pattern distortion by presence of other slots on the substrates is negligible. The relatively high level of sidelobes is likely to be caused by multiple reflections at the complex surface of a metal fixture holding the lens. We plan to investigate origin of the sidelobes in more detail and optimize design of the antenna fixture for future experiments.

CONCLUSIONS

Slot antenna array on a quartz substrate in combination with a plastic lens is a promising solution for low-cost automotive radar with beam scanning capability. Individual antenna slots and a slot array for operation at 24GHz have been designed and manufactured using thin-film technology. Measurements of antenna bandwidth, beamwidth, and beam deflection pitch show good agreement with theory. Our future plans include optimization of the substrate lens system to minimize sidelobe level and evaluation of discrete beam scanning at 77GHz.

REFERENCES

[1] G.M.Rebeiz, “Millimeter-wave and terahertz integrated circuit antennas”, Proceedings of IEEE, 80(11), pp. 1748-1770, November 1992.

[2] D.F.Filipovic, S.S.Gearhart, G.M.Rebeiz, “Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses”, IEEE Trans. on Microwave Theory and Techniques, 41(10), pp. 1738-1749, October 1993.

[3] D.Chouvaev, *Normal metal hot-electron microbolometer*, Ph.D. thesis, Chalmers Univ. of Technology, Göteborg, Sweden, 2001.

[4] X.Wu, G.V.Eleftheriades, T.E.van Deventer-Perkins, “Design and characterization of single- and multiple-beam mm-wave circularly polarized substrate lens antennas for wireless communications”, IEEE Trans. on Microwave Theory and Techniques, 49(3), pp. 431-441, March 2001.

[5] D.F.Filipovic, G.P.Gauthier, S.Raman, G.M.Rebeiz, “Off-axis properties of silicon and quartz dielectric lens antennas”, IEEE Trans. on Antennas and Propagation, 45(5), pp. 760-766, May 1995.

[6] J.-F.Züricher, F.E.Gardiol, *Broadband Patch Antennas*, Artech House, 1995. ISBN 0-89006-777-5.

[7] T.-F.Huang, S.-W.Lu, P.Hsu, “Analysis and design of coplanar waveguide-fed slot antenna array”, IEEE Trans. on Antennas and Propagation, 47(10), pp. 1560-1565, October 1999.

[8] C.A.Balanis, *Antenna Theory: Analysis and Design*, New York: Wiley, second edition, 1997.