Miniature Sensor Node with Conformal Phased Array

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Abstract. *This paper reports on the design and fabrication of a fully integrated antenna beam steering concept for wireless sensor nodes. The conformal array circumcises four cube faces with a silicon core mounted on each face. Every silicon core represents a 2 by 1 antenna array with an antenna element consisting of a dipole antenna, a balun, and a distributed MEMS phase shifter. All these components are based on a single wafer process and designed to work at 17.2 GHz. Simulations of the entire system and first results of individual devices are reported.*

Keywords

Conformal array, sensor node, miniaturization.

1. Introduction

Many vital parameters of airborne systems require a continuous monitoring of signals coming from sensors placed all over an aircraft. Wireless sensor nodes allow building a flexible network of various sensors, communicating with each other and/or with a central control system, while omitting heavy wiring to a cabin computer (Fig. 1). A sensor node utilizing an adaptive steerable antenna array enables electronically controlled network reconfigurability. This can be done by reorganizing the connections through redirection of the antenna beam. This may greatly improve the reliability of the whole sensor network. Indeed a sensor node consists of different functional layers such as a radio system, a processing unit, a sensor, a power storage unit and possibly even an energy scavenging system. We propose a conceptual RF radio subsystem for an ultra small sensor cube with dimensions of 1 cm^3, which is based on a combination of system-on-chip (SoC) solutions.

Although it is a standard approach for traditionally sized beam steered arrays [1], using discrete components such as a feeding network, phase shifters, and antennas is inapplicable for building an efficient and yet very small phased array. Moreover, although several technologies are available to fabricate antennas [2], [3], integrating all these components on the same substrate allows miniaturizing the system, avoiding extra losses and high packaging cost.

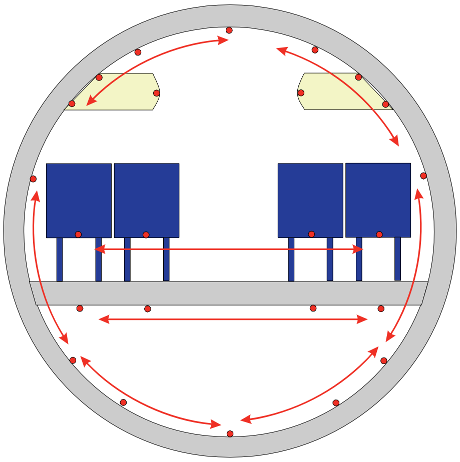

Fig. 1. Placement of sensor nodes in cabin of an air plane. Sensor nodes are able to communicate with each other. Arrows indicate communication direction.

Recently developed RF-MEMS switches, varactors and phase shifters gained a lot of popularity for their integration in radar systems [4]. By integrating RF-MEMS switches with a diversity antenna on one substrate an electrically controlled switched beam was demonstrated in [5], [6]. In order to achieve a more flexible electronic beam steering, in [7] the authors propose a monolithic integration of 3-bit MEMS (Micro-Electro-Mechanical Systems) distributed transmission lines (DMTL) on one substrate with a 1 by 4 antenna array. Relatively narrow beam steering angles of ± 40 deg. were reported with a main lobe degradation while it is steered away from the antenna broadside direction. A mechanical solution does not have the gain degradation for the steered beam, but it is more complex in fabrication and it may be sensitive to any external vibration [8]. The proposed conformal phased array consists of 8 antenna elements which are integrated together with RF-MEMS switches and phase shifters on four independent Si cores (Fig. 2). This array disintegration in four smaller chips decreases fabrication price while improving yield and, most importantly, enables electronic beam steering fully around a cubical sensor node in XZ plane (Fig. 2).

Detailed information on the realization of the cubical antenna topology can be found in [9].

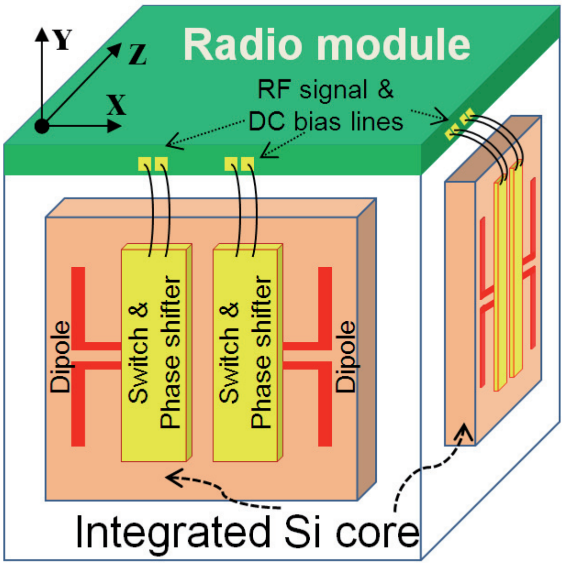

Fig. 2. Schematic view of the wireless sensor node.

2. Concept of the Beam Steering

A sketch of a single Si chip containing two sections including a microstrip dipole antenna, a balun with CPW-to-CPS (CoPlanar Stripline) transition, a real time phase shifter and a MEMS-based RF switch is depicted in Fig. 3. The antenna design (see Fig. 4) has been optimized to have a good matching and return loss (40 dB) at the desired frequency (17.2 GHz) using a passivated high resistivity (HR) silicon substrate ($\varepsilon_r = 11.9$) of 300 µm [10]. The level of the cross-polar component remains below -15 dB in the angular sector of interest (upper hemisphere). The balun has been designed to provide a right angle transition from the coplanar waveguide (CPW) of the phase shifter to the CPS feeding line of the dipole antenna.

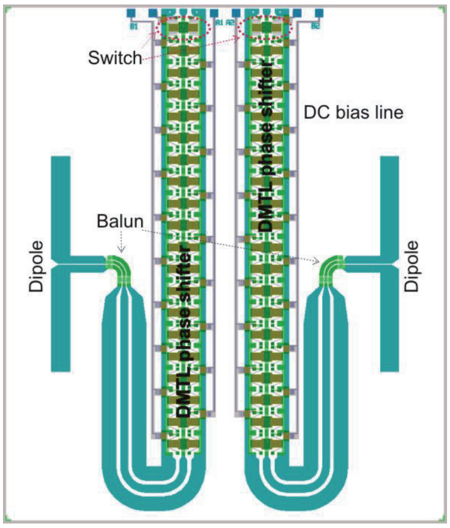

Fig. 3. Integrated 1x2 antenna array on a single chip.

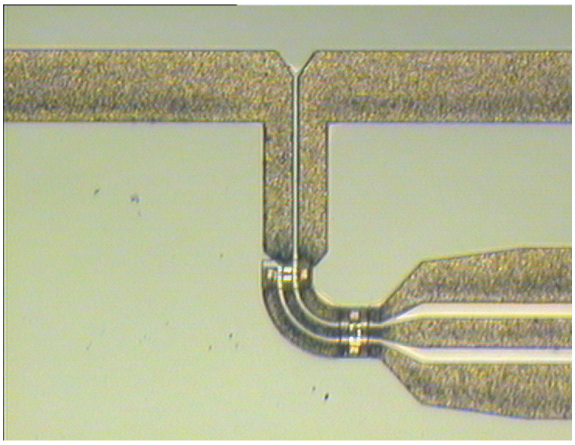

Fig. 4. Detailed photo of the feeding of the dipoles.

By controlling the phase delay to each dipole of the 1x2 array in Fig. 3 a beam steering away from broadside can be achieved. The mutual placement of these four Si cores with the 1x2 antenna array is such that every dipole antenna is situated in a corner of an octagon. This octagon cuts four planes of the sensor node forming a conformal antenna array.

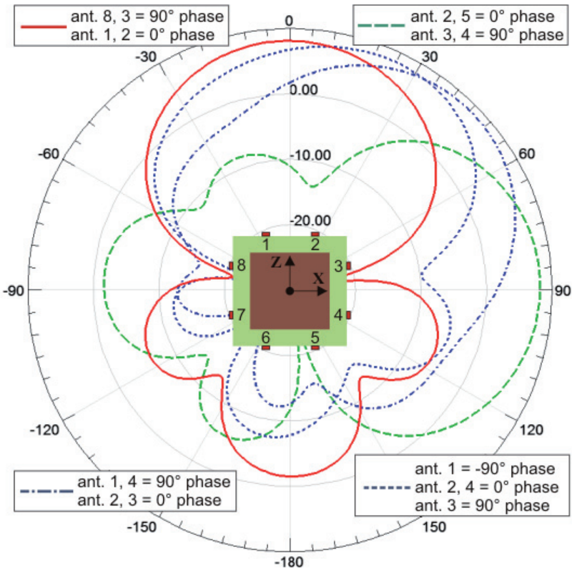

Fig. 5. Simulated gain of the conformal array for different phase delays of four working antennas.

Only four antenna elements are working at a time for achieving a full circular beam steering in XZ plane around the sensor node (Fig. 2). The other four antenna elements are disabled by RF-MEMS switches. All ON elements have the same excitation amplitude. This simplifies complexity in the cube i.e. only switching elements and phase shifters are needed and no variable gain amplifiers or tunable attenuators. The phase of the ON-elements is optimized to realize a maximum gain for a certain radiation angle. For the given sensor size of 1cm^3 the 3dB beam width is always more than 40 degrees. Therefore to provide a uniform circular beam steering around the cube the beam should be tilted with a step of 22.5 degrees. Radiation patterns of the array, simulated in Ansoft HFSS, are demonstrated in Fig. 5. The gain of the steered beam remains constant within a level of 8.2-8.5 dBi.

3. Monolithic Integration of the Phase Shifter and Its Performance

The phase shifter is realized using a DMTL digital approach which consists of a CPW periodically loaded by capacitive MEMS switches. The whole system is fabricated using a 10 kΩcm P-type HR Si substrate.

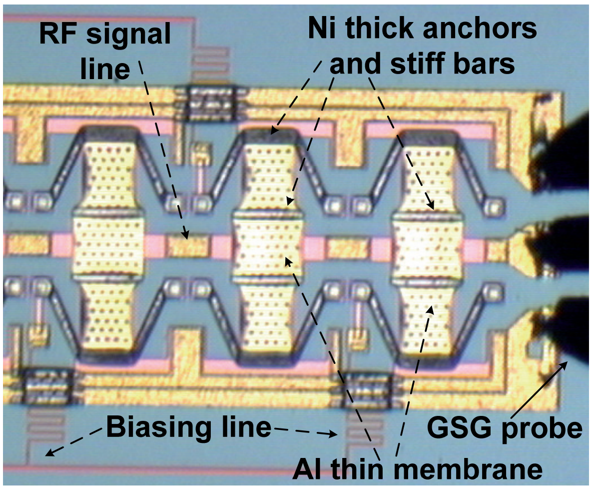

Fig. 6. Top view of the DMTL loaded in a CPW.

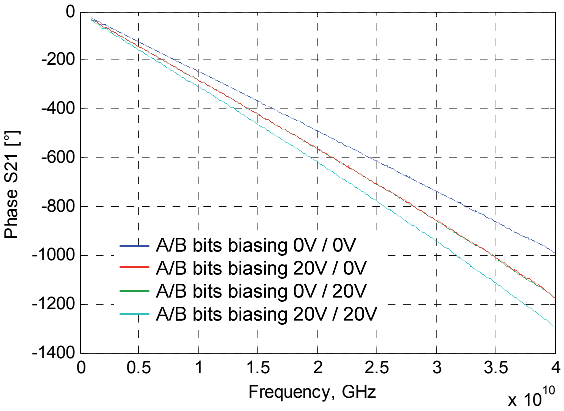

Fig. 7. Measured S21 argument in different bias states.

A seven-mask process described in [11] in detail is used. CPWs and the dipole antenna are made of sputtered 3 µm Al. Al also acts as structural material to anchor the suspended MEMS and air bridges of the balun and the phase shifter (Fig. 6). The top movable electrode is composed of a thin sputtered Al (1.5 µm) and thick electroplated nickel (Ni) (5 µm) is used for the anchoring, the non-movable air bridges, and the stiff bars to avoid deformation of the thin membrane.

Initially a standalone phase shifter was characterized and measured. The pull-in voltage of all the switches of the DMTL starts at about 17 V bias voltage.

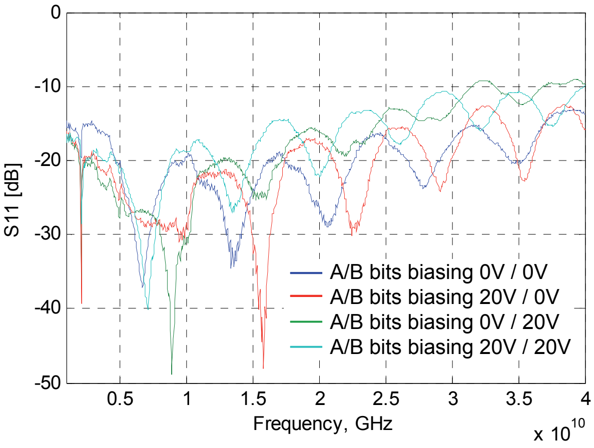

Fig. 8. Measured reflection coefficient of the phase shifter in different bias states.

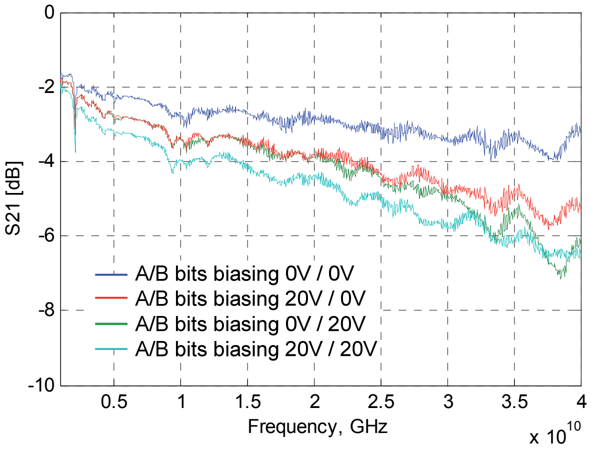

Fig. 9. Measured pass loss of the phase shifter in different bias states.

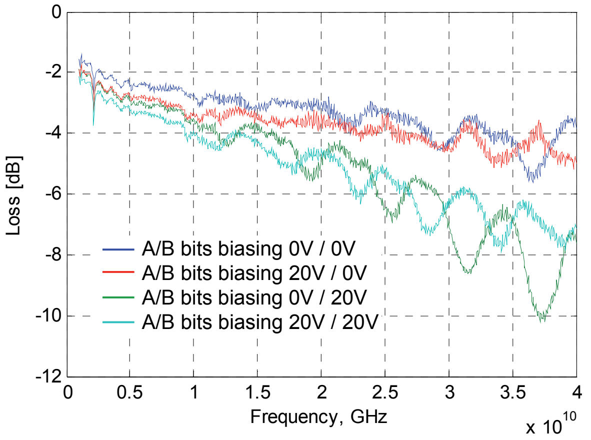

Fig. 10. Measured losses of the phase shifter in different bias states.

Fig. 7 shows the phase delay provided by a DMTL for various bits activation. The measured S11 and S21 are presented in Fig. 8 and Fig. 9 respectively. The total losses in the phase shifter in the Up and Down states are measured to be 3 dB and 5 dB (Fig. 10), which comes to 4.9 dB/mm and 0.82 dB/mm losses respectively.

4. Antenna Theoretical and Experimental Results

A Printed Circuit Board (PCB) was designed for measurements of the single chip with two integrated dipoles. This board delivers both RF signal as well as DC biasing of the phase shifters and the RF switch.

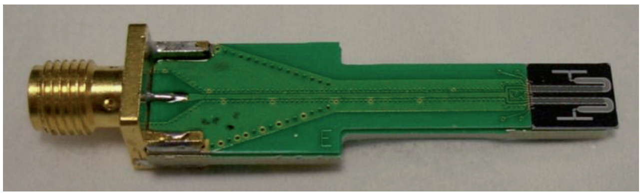

Fig. 11. Ready for measurement integrated 1×2 antenna array on the PCB holder.

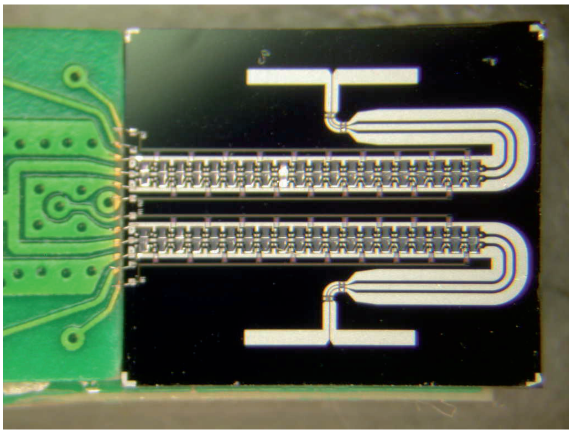

Fig. 12. Top view Si chip with RF and DC signals supplied via bonding wires.

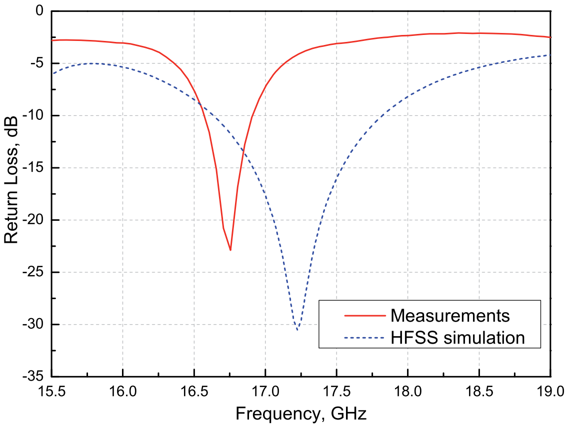

Fig. 13. Reflection coefficient of the two integrated dipoles fed in parallel.

Simulated and measured reflection coefficient of the two integrated dipoles fed in parallel is shown in Fig. 13. The measured resonance is shifted 2.6 % lower in frequency from the designed 17.2 GHz during simulations in HFSS. This frequency shift can be attributed to some imperfections during the assembly of the PCB holder and the Si chip. Parasitic inductances of the bonding wires are also lowering the resonance frequency. All this will be taken into account and compensated for in the further designs. Fig. 14 demonstrates the measured radiation pattern in H-plane at the resonance frequency of 16.75 GHz. The two dipoles are fed in phase and therefore have a main beam pointed at the broadside of the Si chip. A good cross polarization isolation of about 30 dB is measured at broadside.

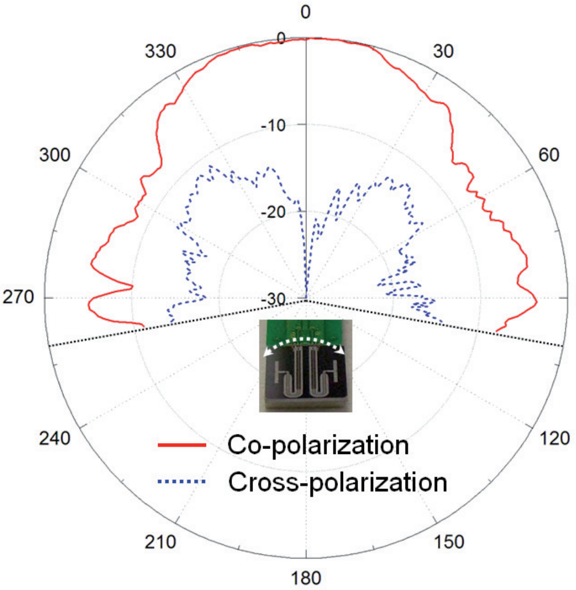

Fig. 14. Measured radiation pattern (H-plane) of the 1×2 antenna array at 16.75 GHz.

5. Conclusions

In this paper we have presented the design of a sensor node conformal phased array. Its beam steering concept was validated by full antenna array simulations with 8 antenna elements. A subarray cell consisting of two RF paths and two antennas was measured in unbiased states. The 1 × 2 array cell shows a good matching with a slight shift of the working frequency (2.6 %). The measured radiation pattern at broadside is quite symmetrical and provides a good polarization isolation. This demonstrator of monolithic implementation of a phased array on a single substrate will be elaborated by increasing the number of 1 × 2 antenna cells in order to achieve full circular beam steering around the sensor node. Since recently, the technology to realize the cubical node has been completed, the next step is to integrate four 1x2 array cells into this cube, realizing a full prototype.

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Guy A. E. VANDENBOSCH was born in Sint-Niklaas, Belgium, on May 4, 1962. He received the M.S. and Ph.D. degrees in Electrical Engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1985 and 1991, respectively. Since 1993, he has been a Lecturer, and since 2005, a Full Professor at the same university. His research interests are in the area of electromagnetic theory, computational electromagnetics, planar antennas and circuits, electromagnetic radiation, electromagnetic compatibility, and bio-electromagnetics. Guy Vandenbosch has been a member of the "Management Committees" of the consecutive European COST actions on antennas since 1993, where he is leading the working group on modeling and software for antennas. Within the ACE Network of Excellence of the EU (2004-2007), he was a member of the Executive Board and coordinated the activity on the creation of a European antenna software platform. Currently he is also the chair person of the IEEE-AP/MTT Benelux section.

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Walter DE RAEDT graduated in Electrical Engineering (1981) at KU Leuven, Belgium. From 1981 until 1984 his research focused on ebeam technology at KU Leuven labs. In 1984 he joined IMEC at its start as a project leader in charge of submicron technologies for advanced HEMT devices until 1997. In 1987 he was visiting scientist at IBM Rüschlikon working on fast III-V circuits. From 1997, he joined the MCM group at IMEC in charge of the design, modeling and characterization activities for packaging. Currently he is head of the RFCDM group at IMEC and was involved in many EU research projects (MIPA, 3DμTune, Shift, e-cubes…). In 2003 he received the IEEE microwave prize with his team. He authored and coauthored more than 200 papers, several patents and book chapters in the field of microwave/mmwave modeling, design and packaging. His current interests are in the field of MEMS-based solutions and SiP (System in package) integration for wireless systems.

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