Conformal Phased Array for a Miniature Wireless Sensor Node

Alexander Vasylchenko¹, Montserrat Fernández-Bolaños², Steven Brebels¹, Walter De Raedt¹ and Guy A. E. Vandenbosch³

¹ RF-CDM group, IMEC, Leuven, 3001 Belgium
² Nanoelectronic Device Laboratory (NanoLab), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, CH-1015, Switzerland
³ ESAT-TELEMIC, K. U. Leuven, Kasteelpark Arenberg 10, Leuven, B-3001, Belgium
E-mail: alexander.vasylchenko@imec.be

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. First results of individual devices are reported and simulations of the whole concept are originally presented.

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 while omitting heavy wiring to a cabin computer. A sensor node utilizing an adaptive antenna array enables electronically controlled network reconfigurability what greatly improves a reliability of a whole sensor network. Indeed a sensor node consists of different functional layers such as a radio system, a processing unit, a sensor, power storage unit and even an energy scavenging system. We propose a concept of RF radio functional subsystem for an ultra small sensor cubes with dimensions of 1 cm³ which is based on a combination of system-on-chip (SoC) solutions.

A general approach of using discrete components such as a feeding network, phase shifters and antennas is inapplicable for building an efficient and yet very small phased array. Integrating all these components on the same substrate allows miniaturizing the system, avoiding extra losses and high packaging cost. Recently developed RF-MEMS switches, varactors and phase shifters gained a lot of popularity for their integration in radar systems [1]. By integrating RF-MEMS switches with a diversity antenna on one substrate an electrically controlled switched beam was demonstrated in [2–3]. To achieve a more flexible electronic beam steering in [4] authors proposed a monolithic integration of 3-bit MEMS 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 main lobe degradation, while it is steered away from antenna broadside direction. A mechanical solution does not have a gain degradation of the steered beam but is more complex in fabrication and may be sensitive to any external vibration [5]. 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. 1). This array disintegration in four smaller chips decreases fabrication price while improving yield and most importantly enables an electronic beam steering fully around a cubical sensor node in XZ plane (Fig. 1).

2. CONCEPT OF THE BEAM STEERING

A sketch of a single Si chip containing two sections including a microstrip dipole antenna, a balun with CWP-to-CPS transition, a real time phase shifter and a MEMS-based RF switch is depicted in Fig. 2. The antenna design 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 [6]. 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.

![Image](image1.png)

**Fig. 2.** Top view of an integrated 1x2 antenna array on a single Si chip.

By controlling the phase delay to each dipole of the 1x2 array in Fig. 2 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 circumcises four planes of the sensor node forming a conformal antenna array.

![Image](image2.png)

**Fig. 3.** 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. 1). 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 so that only switching elements and phase shifters are needed and no variable gain amplifiers or tunable attenuators. The phase of the switched 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. A simulated in Ansoft HFSS radiation pattern of the array is demonstrated in Fig. 3. The gain of the steered beam remains constant within levels of 8.2-8.5 dBi.

2. 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.

![Image](image3.png)

**Fig. 4.** Measured S21 argument in different bias states.

A seven-mask process described in [6] 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. 3). The top movable electrode is composed of a thin sputtered Al (1.5 µm) and a thick nickel (Ni) electroplated (5 µm) using for the anchoring, non-movable air bridges and 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. 4 shows the phase delay provided by a DMTL for various bits activation. The measured S11 and S21 are presented in Fig. 5 and Fig. 6 respectively. The total losses in the phase shifter in the Up and Down states are measured to be 3 dB and 5 dB (Fig. 7), which comes to 4.9 dB/mm and 0.82 dB/mm losses respectively.

3. ANTENNA THEORETICAL AND EXPERIMENTAL RESULTS

A PCB board 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.

Simulated and measured return loss of the two integrated dipoles fed in parallel is shown in Fig. 10. 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, which also lowering the resonance frequency, have to be compensated in the further designs. Fig 11 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 broad side.
4. CONCLUSIONS

In this paper we have presented a design for a conformal phased array. Its beam steering concept was validated by a full antenna array simulation with 8 antenna elements. A subarray cell consisting of two RF paths and two antennas was measured in unbiased states. The $1 \times 2$ array cell showed a good matching with a slight shift of the working frequency (2.6 %). The measured radiation pattern at broadside is quite symmetrical and provided a good polarization isolation. This demonstrator of the monolithic implementation of a phased array on a single substrate will be elaborated by increasing the number of $1 \times 2$ antenna cells in order to achieve full circular beam steering around the sensor node.

5. ACKNOWLEDGEMENT

Authors would like to thank all partners involved in the demonstrator fabrication within the e-CUBES integrated project, which was supported by the 6th European framework program.

5. REFERENCES