RF MEMS Steerable Antennas for Automotive Radar and Future Wireless Applications (SARFA)

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• Summary
RF MEMS = micromechanical devices interacting with electrical signals, with near-ideal signal properties
switching, filtering, modulating, tuning, matching...

near-ideal signal performance
- linearity
- insertion loss
- isolation
- bandwidth
- Q-factor

Variety of applications:
- low-cost to high-end
- consumer to space
- low-volume to high-volume
- DC → RF → sub-mm wave
- telecom
- automotive
- test & measurement
- remote sensing (radar)

Examples: switches:
- insertion loss: <0.1 dB@30 GHz
- isolation: >50dB@2 GHz, >30dB@30 GHz
- linearity: IP3>65dBm
- bandwidth: DC ... >100 GHz

resonators:
- Q=11555@1.5GHz
- Q>80000@13MHz
- >115dB/Hz@10kHz
- ageing 0.15ppm/a
Motivation: Why RF MEMS?

- better performance, new functionality
- applications moving to higher frequencies
  ⇒ RF MEMS: the higher the frequency, the more the benefits
  ⇒ new concepts of “microwave MEMS”
- increasing complexity of RF front-end
  ⇒ re-configurability needed

The solution selected by the telecom industry is RF MEMS switches.

Long term market estimation 2007-2015
RF MEMS to take 23% of the FEM RF semiconductor & antenna markets by 2015
Automotive Radar

• EU initiative: reduce fatal road accidents by 2010 by 50%

• automotive safety systems:
  passive safety → active safety → accident avoiding
  ⇒ shift from crash → pre-crash → accident avoiding sensors

• automotive radar:
  key sensor for accident avoiding/driver assistance
  – EC allocated a temporary band at 24 GHz (Jan 17, 2005)
  – 24 GHz replaced by 77 GHz (Jan, 2014)
Automotive Radar: Problems

• 77 GHz: current systems not mature yet:
  - expensive
  - low-performance, high losses
  - fixed.switched-beam
    ⇒ no object classification, low resolution
    low sensor benefit/responsibility

• price targets:
  - current fixed beam radar sensors in high-end cars cost >2000 EUR
  - cost target for radar sensor system in a mid-range car:
    • current 24 GHz technology: 200 USD
    • future 77 GHz technology (2014): 100 USD
      (sensor: <20 USD ...)
new RF MEMS device concepts as an enabling technology for high-performance, inexpensive millimeter-wave beam-steering/scanning front-end

SARFA: Objectives

- multi-beam steerable beam
- re-configurable, high-capacity communication links
- surveillance radar
- security
- medical: mmW radiometry
- industrial radar
Project Partners

Norway
- NTNU Trondheim
- SensoNor/Infineon
- Ericsson
- Triad

PI: 2 234 000 NOK
PII: 3 868 000 NOK

Finland
- TKK Helsinki
- Elekrobit MW (<2008)
- DA Design (>2008)

PI: 298 000 EUR
PII: 480 000 EUR

Sweden
- KTH Stockholm
- Silex
- MicroComp Nordic
- Autoliv
- Volvo TEC

PI: 3 056 000 SEK
PII: 5 223 000 SEK

Total budget:
EUR 2.38m
(2006-2010)

-Jens Hjelmstad (30%)
-Stein Arne Askeland (PhDstd)
-Shimul C. Saha (PDF 30%)
-Joachim Oberhammer (30%)
-Nutapong Somjit (PhDstd)

-Antti Räisänen (10%)
-Dmitry Chicherin (PhDstd)
-Sergey Dudorov (sen.35%)
-Dmitri Lioubtchenko (sen.25%)
Project Constellation

• partners with complementing competences
  – TKK: RF & millimeter-wave devices
  – KTH: RF MEMS device design, fabrication, evaluation
  – NTNU: radar sensor and system technology

• SARFA is addressing different industrial groups, supporting the project:
  – automotive (Volvo TEC, Autoliv, SensoNor Infineon)
  – MEMS (Silex, SensoNor Infineon)
  – telecommunication & industrial mw applications
    (MicroComp Nordic, Elektrobit)
  – remote sensing/radar (Triad, Ericsson)

• true interdisciplinary project:
  – MEMS
  – microwave/millimeter wave engineering
  – telecommunication
  – radar technology
  – automotive electronics

• hardware fabrication/characterization, system modelling
Vertical Approach

– novel microwave MEMS beam-steering components:
  • MEMS high-impedance surfaces for
    - tuneable reflective surfaces
    - re-configurable leaky-wave antennas
    - low-loss waveguide phase-shifters
  • MEMS low-loss re-configurable dielectric-block phase shifters
  • 3D micromachined, substrate-embedded high-directivity antennas

– sub-system approach:
  • wafer-scale integration of phase-shifters and high-directivity antennas

– system level:
  • investigation of system implications of RF MEMS technology to radar sensors
  • exploitation of the technology platform for other applications: industrial radar, security applications and future high-capacity sub-millimeter wave communication links
**Work Package 1+2:**

MEMS Tunable High-impedance Surfaces for  
- WP1: low-loss phase-shifters  
- WP2: beam-steering by tuneable reflective surfaces and leaky-wave antennas
Electronic Beam Steering using MEMS High-Impedance-Surface Meta material surface: surface properties not existing in nature

Resonance frequency:

$$\omega_0 = \sqrt{1/(LC)}$$

El-magn wave surface impedance:

$$Z_s \to \pm j\infty$$

Reflection coefficient el-magn wave:

$$R = \frac{Z_s - \eta}{Z_s + \eta} \quad \angle R : +180^\circ \to -180^\circ$$

$|R| :$ ideally constant

$\Rightarrow$ ideal phase-shifter!
Electronic Beam Steering using MEMS-HIS

Local tuning of surface resonance frequency
⇒ local phase-shift of reflection coefficient
⇒ phase distribution/gradient possible
⇒ beam-steering as tuneable reflective surface
⇒ single chip substitutes large subsystem in beam-steering unit
Different Embodiments

Indirect beam steering:
- reflective-type tuneable high-impedance surface

Waveguide embedded phase shifters:
- tunable high impedance surface integrated in waveguides wall:
  low loss, analogue phase shift

Direct beam steering:
- steerable leaky wave antennas
Prototype Devices (April 2008)

200×52 array

single element
Microwave Characterization

simulation results

measurement results

measurement set-up at TKK, FI

first fabricated and characterized MEMS tuneable metamaterials!!!
Work Package 3:

MEMS Tuneable Dielectric-Block Phase-shifters and Wafer-scale integrated High-Directivity antennas
Beam Steering with Phase-shifter Networks and Antenna Arrays

**Problems:**
- conventional MEMS phase shifters only for low power signals
- switched line phase-shifters not suitable for W-band (75-110 GHz)

**Conventional MEMS approach:**
phase shifters + in-plane antenna array
Novel RF MEMS Phase-Shifter Approach

- power limitation of conventional MEMS phase shifters because of thin, moving metal bridges
- new approach: tuning of the wave propagation velocity by electromechanically moving of dielectric load block

\[ \Delta \phi = 45^\circ \]

\[ \varepsilon_{\text{eff}} \approx \varepsilon_{\text{eff,0}} \]

\[ \Delta \phi = 135^\circ \]

\[ \varepsilon_{\text{eff}} \gg \varepsilon_{\text{eff,0}} \]

\[ \Delta \phi = 180^\circ \]

L = \lambda / 2

\[ \Delta \phi = 45^\circ \]
Taylor-made Dielectric Material

- multiple stages needed for full 360° capability:
  ![Diagram showing multiple stages with alternating widths and lengths.](image)
  \[ \frac{\lambda}{2} \]

- binary coding to decrease number of stages
  ![Diagram showing binary coding pattern](image)
  \[ \frac{\lambda}{2} \]

- requires integration of different thick-film materials with different permittivity on the same wafer ...

- solution: etch-hole pattern
  ⇒ artificially designed varying local permittivity in same material
  ⇒ tailor-made propagation speed

\[ \lambda \]
\[ \frac{\lambda}{2} \]
Prototype Fabrication & Evaluation

WP3

(a) Up-state

(b) down-state

45°

30°

15°

Return and insertion loss (dB)

Frequency (GHz)

Insertion loss
Return loss

Phase difference, µ degrees

Frequency (GHz)
W-band performance better than any previously reported work!

- 7 stage 45° ⇒ full 360° capability
- W-band performance:
  - single stage: IL<1.7dB, RL>15dB
  - 7 stage: IL<4dB, RL>12dB ⇒ 74.1°/dB, 592.1°/cm (72GHz)
Work Package 4:

Investigation of System Aspects of RF MEMS Technology on Radar Sensors
Focus WP4

- approach from system level
- identification of applications beside automotive radar
- assessment of specifications in different applications
  - automotive radar (76-81 GHz)
  - industrial radar
  - security applications
  - point-to-point communication links (60, >100 GHz)
- investigation of implications of RF MEMS technology on system design

Current Activities

- developing component models from measurement data of the phase-shifters
- developing far-field model of the micromachined antennas
- implementation of the models in system models
A few management highlights

• Steering Group Meetings:
  – 3 industrial members: SensoNor (NO), Silex (SE, PI), µComp Nordic (SE, PII), Elektrobit (FI, until Nov. 2008), DA-Design (FI, nominated from Dec. 2008)
  – 5th Steering Group + technical meeting tomorrow
  – average number of participants:
    3.2 industrial; 6.2 academic; 0.2 funding agency

• 9 accepted scientific publications + 3 master thesis

• researcher exchange benefit:
  – fabrication phase: TKK visited KTH
  – measurements: KTH -> TKK

• webpages continuously updated:
  www.sarfa.ee.kth.se

• we like Scandinavian projects, but ...
  – one spin-off EU project based on WP1+WP2
  – involvement in another EU automotive radar project
EU Spin-off

“TUMESA” (EU FP7):
MEMS Tuneable Metamaterials for Smart Wireless Applications

- TKK (coordinator)
- KTH
- Univ. Rennes I
- µComp Nordic
- TRW/Autocruise

June 2008- Mai 2011
Budget: EUR 2.53m (1.85 EU)

Participants (5):

TKK (coordinator)
KTH
Univ. Rennes I
µComp Nordic
TRW/Autocruise

SARFA

Research partners (5):

“ADOSE” (EU FP7):
Reliable application specific detection of road users with vehicle on-board sensors

- VTT (FI), UU (SE), Triad (AS), IMEC (BE), STMicroelectronics (IT), FhG(DE), Bosch(DE), UMICORE(BE), Magneti Marelli(IT), FIAT(IT), EPE(GR), Austria Research Center (AT)

Budget: EUR 10.2m (6.1 funded)

According to Triad, their involvement in SARFA was a key criteria to qualify for their project participation.

Content:
- sensor fusion, sensor network
- advanced driver assistance systems

SARFA
Summary

- general remarks:
  - research topic (millimeter wave beam-steering) important for increasing number of safety, security, medical, telecom, industrial applications
  - addressing different industrial groups in Scandinavia (automotive, telecom, MEMS)
  - very hardware related research in FoB of successful production companies in all NORDITE countries
  - system aspects of new hardware platform investigated

- 2008 very successful for SARFA:
  - first MEMS prototypes finished in all hardware WP
  - characterization successful!
  - closer collaboration with NTNU: system level modeling based on measurement results
  - drastic increase in publication output:
    - publications increased from 5 → 9
    - master thesis reports increased from 1 → 3
  - spin-off EU project + involvement in EU radar project
Comments: NORDITE Programme

- NORDITE is filling a gap between direct industrial collaborations and large European projects
- medium size projects very efficient and flexible
- NORDITE provides "critical mass" of funding:
  - allows to carry out “senseful” research efforts
  - allows for starting new activities, not just "additional funding" for continuing existing research
- driven by needs of industrial supporters
- researcher exchange=very beneficial, especially in interdisciplinary projects, but difficult to implement in practice
- positive experience with NORDITE partners may trigger future collaborations
Work Packages Overview

WP 3
System aspects of MEMS based radar front-end

WP 2
Phase shifters and Integration with antennas

WP 1
Phase shifters based on MEMS tunable surfaces

system level
component/subsystem level
component level
vertical approach

man months
TKK KTH NTNU
MEMS Tunable HIS Design

- TKK: microwave simulation & design
- KTH: electro-mechanical simulation & design, layouting