A Lightweight, 64-element, Organic Phased Array with Integrated Transmit-Receive SiGe Circuitry in the X Band

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Once Upon a Time in the North Pole…

Pictures from “Polar explorers struggle across Arctic ice to measure impact of global warming”, available online at www.dailymail.co.uk (March 2009)
Near Future Goal (Concept)

Unmanned Air Vehicle with lightweight phased array for radar surveying
Source: nasa.gov

Survey Results: 3D model of the ice layer
Source: National Geographic
The Purpose of this Work

- To develop a high-performance, low-cost and lightweight transmit/receive (Tx/Rx) phased array for efficient unmanned ice-survey studies in X-band.
- X-band radar will be part of sensor suite.

8-16 GHz (2006)

9.5 GHz (This Work)
3-D SOP Approach

- Multilayer Organic Technology
- Embedding of Low Cost SiGe and RF MEMS Electronics
- Back-end Electronics and Control Using FPGA Technology
Agenda

• SiGe RF Circuits
• Phased Array Features
• System Components
• Performance Test Results
• Conclusions
Phased Array Features

Integrated High Performance

- Transmit Receive Operation
- Computer Driven Beam Steering
- Silicon Germanium Integrated Circuits
- Low Energy Consumption
- Low Cost, Lightweight
  - Silicon-based Circuitry (MEMS, Tx/Rx IC)
  - Organic Substrates (LCP/Duroid)
Phased Array Design Radio Frequency Specifications

• Center Frequency 9.5 GHz
• Target Bandwidth: >500 MHz
• Equal-gain Beam Steering Range: ± 26°
• Transmit/Receive Capability
GT team is developing the entire radar system

1 SiGe+MEMS chip per array column (=8 antennas)

Radar Block Diagram

Antennas

Beamformer

MEMS T/R Switch chip

SiGe chip

LNA

spc

T/R duplexer

Phase shifter

PA

Beamformer

Radar Back End (Down/Up Conversion and Local Oscillators)

Control FPGA (for SiGe ps)

DC Power Supply & Distribution Boards

Laptop for master control & processing

Front End
Self-biased PA

• Class AB PA with self-bias network
• 15 dBm Pout at 9.5 GHz
• Designed for robust, uniform performance across array
Self-biased PA simulations

15 dBm Pout @ 9.5 GHz

Peak Gain = 23.3 dB

PAE = 30.7%
SiGe T/R Chips

Integrated T/R
LNA, PA, duplexer switch
CMOS phase shifter, and digital logic

IBM 8HP Process

Block Diagram
TR Module

Photo of the TR Module
Layout of T/R Chip
Board Level Rx SiGe Characterization

Measured Rx path in the mounted on LCP/Duroid board →

Measured Rx path on Chip
Antenna Board: Overview

Patch-Antenna Side
- Power Amplifier
- Patch Antennas

Beam-former Side
- Beam Steering Direction

RF Feed
- ROW #8
- ROW #7
- ROW #1

TRIC
- Phase Shifter
- BiCMOS Switch
- Low Noise Amplifier

MEMS Switch
Antenna Board Dimensions

Dimensions:
30.4 cm x 25.4 cm
[11.9 in x 10 in]

Thickness:
1.52 mm
[60 mil]

Weight:
184.7 g
[6.5 oz]
• Beam former: Rogers 3850 Liquid Crystal Polymer (LCP)
• Patch Antenna Substrate: RT/Duroid 5880 LZ
Antenna Board: Integrated Circuits

- Silicon Germanium (SiGe) Transmit/Receive IC (TRIC):
  - Low Noise Amplifier (LNA)
  - Phase shifter (PS)
  - Tx/Rx BiCMOS Switch
- SiGe Power Amplifier (PA)
- Commercial Micro Electromechanical System (MEMS) switch – RadantMEMS
Digital Control and Power Supplies

• Power Supply Module
  - 2.5 V for antenna-board logic
  - 3.5 V for RF circuitry
  - 5.0 V for MEMS Driver Card

• Digital Control
  - Field Programmable Gate Array (FPGA) controls RF
  - Computer program: human interface for FPGA

• Additional power supply for MEMS actuation (80 V)
Performance Test: Measurement Setup

Antenna Board
DC/Digital Module
Laptop
MEMS Power Supply

Fully Automated Anechoic Chamber

Antenna Board Mount
Measured Radiation Pattern at different Azimuthal Steering angles (Co-Pol, Rx)
Measured Radiation Pattern at different Azimuthal Steering angles (Co-Pol, Tx)
Elevation Scan Results

• 3 dB Beam Width at bore sight: 7.5° (Tx), 7.5° (Rx)

• Max. Side Lobe Level from Peak Gain:
  -12.81 dB (Tx)
  -12.65 dB (Rx)
Phased Array Performance (2)

- **Antenna bandwidth:**
  - 2.430 GHz (Rx)
  - 2.625 GHz (Tx)
  - 2.52 GHz (Average)

- **Bore sight gain at 9.5 GHz:**
  - 27.28 dB (Rx)
  - 18.24 dB (Tx)
### Phased Array Performance (3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured (Rx)</th>
<th>Measured (Tx)</th>
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<tbody>
<tr>
<td>Bandwidth</td>
<td>2.430 GHz</td>
<td>2.625 GHz</td>
</tr>
<tr>
<td>Beam-Steering Range</td>
<td>± 28.0°</td>
<td>± 28°</td>
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<tr>
<td>Energy Consumption</td>
<td>601.3 mW</td>
<td></td>
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<tr>
<td>Max. Cross-Polarization level</td>
<td>&lt;30 dB</td>
<td>&lt;30 dB</td>
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<tr>
<td>Estimated EIRP</td>
<td>--</td>
<td>41.33 dBm</td>
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</tbody>
</table>
Embedded design (under way)

- Wire Bond Package
  - 2-D packaging
  - Convenient
  - High parasitic inductance

- Standard Flip-Chip Package
  - Reduced parasitics compared
  - Increased I/O density
  - Smaller footprint

- Embedded Flip-Chip Package
  - 3-D packaging
  - Near Hermetic
  - Low form factor

Substrate Stack-up showing IC placement

8x8 Transmit Receive
32 Embedded T/R SiGe chips
Flip-Chip Package Comparison (1)
Flip-Chip Package Comparison (2)

- Flip-Chip Package
  - Negligible change in return loss
  - 0.4 dB added loss from FC interconnects

- Embedded Flip-Chip Package
  - Negligible change in return loss
  - 0.6 dB added loss from FC interconnects and via transitions
  - 0.3 dB increase in NF correlates to input package loss
  - Minimum and 50 Ω NF show package is well matched
RF Back-End Boards
Summary

• The T/R operation of an organic 64-element phased array was demonstrated for the first time using SiGe ICs at 9.5 GHz.

• Measurements showed:
  - Rx gain of 27.28 dB
  - Tx gain of 18.24 dB
  - Beam Steering of 60 degrees
  - EIRP of 41.33 dBm

• Further research will focus in bringing SiGe ICs closer to the patch antennas through innovative Packaging Techniques
Thank You

Questions?