Unlocking the mmWave spectrum and enabling the 4th IR
- 5G - from small cells to massive MIMO and the IoT

6th May 2019, IEEE 5G Summit, Pretoria, South Africa
AGENDA
Let’s begin!

Welcome
Glad to be here!

Introduction
What is 5G really? New apps only? What are the key enabling techs?

Market opportunity
What is the problem? Our niche.

Our value proposition
How we will make E-band a coverage spectrum.

Business strategy
What we’ve done and where we’re going.

Q&A
Want to know more?
INTRODUCTION

What is 5G really? New apps only? What are the key enabling techs?
INTRODUCTION
Evolution of 5G

- 1000x Mobile data volumes
- 10x – 100x Connected devices
- 5x Lower latency < 1 ms
- 10x – 100x End-user data rates > 10 Gb/s
- 10x Battery life for low power devices

Source: METIS

1990 Mobility Roaming 9.6 Kb/s
2003 Multi-media 2 Mb/s
2010 Architecture Efficiency 300 Mb/s – 1 Gb/s (LTE-A)
INTRODUCTION

Network as a service – SDN/NFV

Service-driven architecture

- Multiple services, standards & site types
- Multi-connectivity technologies (LTE, WiFi, Fibre)
- On-demand deployment (re-configurability)
- Flexible and fast orchestration of eMBB, uRLLC, mMTC

eMBB
Enhanced Mobile Broadband

10 Gb/s

uRLLC
Ultra-reliable and Low-latency Communications

< 1ms

Smart buildings

Smart-cities

3D video, VR, UHD

Work & play in the cloud

Augmented reality

Industry automation

Mission critical apps

Self driving cars

1 million / km²

mMTC
Massive Machine Type Communications

Source: Nokia
INTRODUCTION

Network as a service – SDN/NFV

CloudRAN

- RAN real-time
- RAN non-real-time

Mobile Cloud Engine (MCE)

- Access network scheduling
- Link adaption
- Power control
- Interference coordination
- Modulation
- Coding
- Beam-forming/steering
- Cognitive radio

- Inter-cell handover
- Cell selection
- UP encryption
- Multiple connection convergence

Service Oriented Core (SOC)

- Universal processing OK

On-site dedicated hardware (close proximity)

Source: Huawei
INTRODUCTION

Key enabling 5G technologies

5G

- mmWave
- Small Cell
- Massive MIMO
- Beam-forming
- Full Duplex
MARKET OPPORTUNITY

What is the problem? Our niche.
The Evolution of 5G

2015
- Macro Base Station
  - Increasing Frequency beyond 2.7GHz to 6GHz
  - Increasing Bandwidth
  - Increasing Efficiency

2016
- Densification
  - Small Cells
  - DAS
  - LTE-U

2017
- Massive MMO & Digital Beam Forming
  - Up to 6GHz
  - Array Antenna

2018
- mmWave
  - 50 to 90 GHz
  - 2.9 GHz available bandwidth
  - 70 to 85 GHz
  - 10 GHz available bandwidth
  - 3.8 GHz
  - 4 GHz available bandwidth
  - 2.8 GHz
  - 2 GHz available bandwidth

2019
- Ultra-wide bandwidth
- Ultra high throughput

2020

Source: Qorvo © 2015 Qorvo, Inc.

Fibre in the air!
E-BAND - THE NEXT FRONTIER (70-120 GHZ)

Why focus on E-band?

Gold mine! This opportunity will never appear in the radio spectrum ever again! Ever.
APPLICATIONS AND OUTLOOK

1. 5G Backhaul
2. 5G Fronthaul
3. Fixed wireless access
4. 5G Mobile access
5. Sat to surface
6. Automotive radar

We believe the world will be blanketed by E-band by 2025

Gaps in market:
- No E-band filters on-chip
- DSP – big data problem

Beam forming @ E-band

64x64 > 4000 ICs

MMIMO

Automotive RADAR

Small Cells
MAJOR INDUSTRY PLAYERS THINK SO TOO

Figure 10: New deployment share per frequency range [GHz]

- 6-13
- 15-23
- 26-42
- 60
- 70/80

Traditional bands still represent 70% of new deployments in 2020.

Major growth in E-band – up to 20% in 2020.

Source: Ericsson (2015)
Challenges: size, cost and power consumption. Unfit for small cell/MIMO.
BULKY FRONT ENDS

Wavence
networks.nokia.com/products/wavence

Mini-Link

RTN-380

GX4000

iPASOLINK EX

EtherHaul

Nokia Networks

ERICSSON

HUawei

Fujitsu

NEC

Siklu

DragonWave, E-band communications, Ceragon, Intracom, Airspan, Cablefree, Siae Microelectronica, Lightpointe
1. Small Cell

**Existing solutions: E-band**

- $11k per link
- > 1m² real-estate
- ~ kW of power

\[ X1 \quad \text{Every 50m}^2 = \text{Many MILLIONS} \]

- $ Many Billions
- Millions m² real-estate
- ~ MWs of power

\[ \text{impossible} \]

**BULKY FRONT END PROBLEM**

**SMALL CELLS**

\[ \text{No viable solutions at E-band for true Small Cell densification} \]

**Integrated Microwave Assembly (IMA)**

\[ \text{→ $$$$$} \]
BULKY FRONT END PROBLEM

MMIMO

Existing solutions: 28 GHz, 39 GHz

No solutions at E-band

2. MMIMO

Existing solutions: < 6GHz

A solution like this is needed!

Bulky, expensive, power hungry → No-go

Real-estate? Power? $$$$?
SUMMARY OF EXISTING SOLUTIONS

Current generation front-end IC’s & tech

- BPF
- AMP
- Phase shifter
- MIX
- ADC
- DSP
- 8-bit
- VCO/Synth
- 40 core
- DATA

IMA (Integrated Microwave Assembly)
- Thousands of $
- Manufacturing difficulty
- Low volume
- Power hungry
- Big and bulky

SAW, BAW, waveguide (off-chip) – integration problem

Big-data problem

Infineon BGT70 IMA

* only an e.g. of a possible configuration

Size of a shoe-box
“mmWave will never materially scale beyond small pockets of 5G hotspots in dense urban environments”
-- T-Mobile CTO Neville Ray

“We will need to remind ourselves, this is not a coverage spectrum”
-- Verizon CEO Hans Vestberg

“The roll-out of 5G in the country will be much more case-based”
-- MTN South Africa CEO Rob Shuter

Millimeter-wave 5G isn’t for widespread coverage, Verizon & T-Mobile admit

NO SMALL CELL OR MMIMO E-BAND SOLUTION IN SIGHT FOR MAJOR INDUSTRY PLAYERS!

Built on 5G Challenge

What we're looking for.

Challenge areas
We’re looking for solutions in the categories of Industry (helping businesses create new value for customers), Immersive Experiences (next-generation media and entertainment), and Moonshots (solving big problems with radical new ideas). Every submission should demonstrate the company’s commitment to social responsibility and sustainable business practices.

Basically: they want apps that will make customers use their networks
OUR SOLUTION

We will make E-band connectivity so cheap and small it fits on every lamp-post!
OUR SOLUTION — INTEGRATION IN SILICON

First generation

- Thousands of $ (IMA)

Second generation

- Cheap
- Mass producible
- Low power
- Small

BPF + AMP + MIX + ASP + ADC + DSP = DATA

$63

- Thousands of $

Reduces load on DSP

Cheap

Mass producible

Low power

Small

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**OUR SOLUTION**

- **True SOC**
  - BPF
  - AMP
  - Phase shifter
  - MIX
  - LPF
  - ASP

- **No IMA (or greatly reduced)**
- **Size of a match-box!**

- **Stage 1: value add (evolutionary)**
  - No/less IMA:
    - Mass producible
    - Cheap
    - Small
    - Low power
    - Single chip
    - Perfectly suited for Small Cells and massive MIMO
    - Enhanced performance

- **Stage 2: value add (revolutionary)**
  - Cognitive radio
  - Advanced beam steering (MIMO)
  - DCMA
  - Channel equalization
  - RTFT (Range-Doppler)

- **Our BPF & LPF is in Silicon (gen 1)**
- **Our new ASP (gen 2)**
- **4-bit 1 core DSP**
- **DATA**

*only an e.g. of a possible configuration*
**END PRODUCT COMPARISON**

1. Single-chip TxRx front-end
2. With integrated tunable BPF
3. With analog signal pre-processing
4. This reduces size, cost and power consumption

*not to scale*

We will make Gbps connectivity so cheap it will be on every light pole!

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cheap (&lt; $1000)</th>
<th>Expensive (~ $11,200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Low-power (&lt;&lt; 20 W)</td>
<td>Power intensive (~ 100 W)</td>
</tr>
<tr>
<td>Size</td>
<td>Small (&lt; 5 cm x 5 cm)</td>
<td>Bulky (~ 25 cm x 25 cm)</td>
</tr>
<tr>
<td>Volume</td>
<td>Mass producible</td>
<td>Low-volume</td>
</tr>
</tbody>
</table>

*versus*

```
VALUE PROPOSITION
VALUE PROPOSITION

1. Silicon BPF

Existing solution

5 cm

20 cm

Our solution

300 microns

1 mm

- Size & mass reduction x 100
- Monolithic integration enabled
- BOM reduction from
  - (2-8 individual filters)
  - (8-50 connectors and fasteners)
- No more hand tuning
  - Mass producible (easy to meet market demand)
  - Built in self tuning (BISTu)
- Cost benefits (IMA) – can be thousands of $ per unit
## VALUE PROPOSITION

2. ASP: Real-time Fourier analysis for cognitive radio

<table>
<thead>
<tr>
<th>Multifractal’s solution</th>
<th>SOTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous analogue Fourier transform of a 3–9 ns sample window</td>
<td>Computation time on the order of μs - C674x DSP: 256-pt FFT (16-bit) – 1.55 us, 512-pt FFT (16-bit) – 3.61 us</td>
</tr>
</tbody>
</table>
| Frequency resolution < 0.5 GHz @ Δτ = 3 ns:  
  • 0.3 GHz @ Δτ = 6 ns  
  • 0.1 GHz @ Δτ = 12 ns | Few hundred MHz |
| Continuous bandwidth of 5 GHz per channel | ~30 dB |
| Dynamic range > 35 dB: @ Δτ = 3 ns:  
  • > 40 dB @ Δτ = 6 ns  
  • > 50 dB @ Δτ = 9 ns  
  • 50+ dB @ Δτ = 12 ns  
  • Noise considered | kW |
| Power consumption = 0.1 W (ADC) + ASP (< 50 mW) + x (mixer / mult) + x (LNA x 2) + x (envelope detector) |  |
| Cost: soft substrate – few hundred $ | Thousands of $ |
| Cost: on-chip ➔ cheap CMOS or BiCMOS (few cents per chip mass production) | - |

- Real-time
- No need for FFT
- Large scanning bandwidth
- Low power
- Low-cost

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E.g.: Cognitive Radio

COGNITIVE RADIO THE NEW 5G RADIO

E.g.: Automotive radar

SOTA: resolution of 1m, maximum velocity of 30 m/s, few objects

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3. ASP: Advanced beam forming

- Arbitrary frequency beam steering
  - Steering angle controlled by frequency (carrier)
- Continuously tunable (1 GHz BW - > 60 deg)
- Specialized frequency to beam angle mapping possible
- Low power – 20 mW per phaser (much lower than DSP solutions)
- Low cost – CMOS and BiCMOS – support mass production

Automotive radar

- Multiple objects – SOTA 32
- Wideband DDS can easily allow 60 deg to be mapped over 10 GHz allowing > 200 objects to be mapped each with 50 MHz fc control range
## Generation 1 Front-End (telecoms)

### High-level specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multifractal’s gen 1 front-end</th>
<th>Siklu E-band front-end (EtherHaul 8010FX)</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&lt; 2 W</td>
<td>50 W (including DSP)</td>
<td>10-20X power reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Tens of $</td>
<td>~$ 11k</td>
<td>&gt;100X cost reduction</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>5 GHz</td>
<td>2 GHz</td>
<td>SoC solution – fewer components, higher bandwidth, lower power</td>
</tr>
<tr>
<td>Throughput</td>
<td>10 Gbps full duplex</td>
<td>10 Gbps full duplex (FDD)</td>
<td>-</td>
</tr>
<tr>
<td>RF bands</td>
<td>71-76, 81-86 GHz</td>
<td>71-76, 81-86 GHz</td>
<td>-</td>
</tr>
<tr>
<td>System gain</td>
<td>80 – 98 dB</td>
<td>64 – 93 dB</td>
<td>-</td>
</tr>
<tr>
<td>Range</td>
<td>300 m</td>
<td>2.73 – 3.7 km</td>
<td>Small cell densification</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-45 to +85°C ++</td>
<td>-45 to +55°C</td>
<td>Single chip solution – better temperature performance / match</td>
</tr>
<tr>
<td>Dimensions</td>
<td>~ 10 by 10 cm (with MIMO array) – RF module (~5x5 cm)</td>
<td>~ 30 by 30 cm (single antenna – no MIMO)</td>
<td>Massive MIMO</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 100 g</td>
<td>~ 5 kg</td>
<td>Small, lightweight</td>
</tr>
<tr>
<td>NF</td>
<td>~5 dB</td>
<td>?</td>
<td>Relaxed requirements due to small cell dens.</td>
</tr>
</tbody>
</table>

Smaller range has benefits – our solution allows for this small cell dens. due to lower costs, power and size.
### GENERATION 2 FRONT-END (telecoms)

High-level specifications (ASP only – cognitive radio – other specs stay the same)

---

#### Parameter | Multifractal’s IC | TI’s AWR1243 / DSP 66x series or equivalent | Our value add
--- | --- | --- | ---
Power consumption | < 20 W (incl. DSP) | > 100 W (incl. DSP) | 5-10X reduction
Cost | Hundreds of $ | Thousands $ | >100X reduction
Processing speed | < 50 ns per FFT | > 1 µs per FFT (1 core) | 50X improvement (faster multiple object detection)
IF bandwidth (automotive radar) | 1–4 GHz | 5 MHz | 100X faster (faster detection)
RF bandwidth (automotive radar) | 4 – 8 GHz | 4 GHz | 2X larger → 2X resolution (4.5 cm → 2.25 cm)
Complexity | Final system design = simple/no IMA | Final system design = complex IMA | Supports mass production, lower production costs
Dynamic range | 50 dB | ~ 50 dB | -
ENOB | 4 | 8 | Relaxed ADC requirements
Equivalent n-points | 70 (current technology with the aim to improve) | - | -
Power accuracy | ±3 dB | ~ 1 dB | -
Frequency accuracy | ~ 100 MHz | ~ 100 MHz | -
Magnitude / phase information | Magnitude only | Both | Application dependent

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Existing solution do not scale well with bandwidth

<table>
<thead>
<tr>
<th>Power (mW)</th>
<th>Clock frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>800</td>
</tr>
<tr>
<td>5000</td>
<td>1000</td>
</tr>
<tr>
<td>10000</td>
<td>1200</td>
</tr>
<tr>
<td>15000</td>
<td>1400</td>
</tr>
</tbody>
</table>

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## Generation 2 Front-End (telecoms)

High-level specifications (ASP only – frequency beam steering – other specs stay the same)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multifractal’s IC</th>
<th>TI’s AWR1243 / DSP 66x series or equivalent</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&lt; 20 W (incl. DSP)</td>
<td>&gt; 100 W (incl. DSP)</td>
<td>5-10X reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Hundreds of $</td>
<td>Thousands $</td>
<td>10X reduction</td>
</tr>
<tr>
<td>Processing speed (tracking speed)</td>
<td>&lt; 50 ns per operation</td>
<td>&gt; 1 µs per operation (1 core)</td>
<td>50X improvement (faster steering)</td>
</tr>
<tr>
<td>Complexity</td>
<td>Final system design = simple/no IMA!</td>
<td>Final system design = complex IMA</td>
<td>Supports mass production, lower production costs</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>50 dB</td>
<td>~50 dB</td>
<td>-</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt; 8GHz</td>
<td>4 GHz is already a challenge</td>
<td></td>
</tr>
<tr>
<td>Channels per antenna (frequency mapped to angles)</td>
<td>&gt; 30 (only one array! – one tile)</td>
<td>? (Unheard of) – many tiles / antenna arrays needed</td>
<td>More massive MIMO! Truly big data.</td>
</tr>
<tr>
<td>Frequency reconfigurability (lens effect)</td>
<td>8 GHz band $\rightarrow$ 100 MHz band</td>
<td>Unheard of</td>
<td>Frequency lensing</td>
</tr>
</tbody>
</table>

- **Spatial information:**
  - Dispersive Feeding Network
  - dispersive antenna array (time-space transformer)

- **Temporal information:**
  - $\Delta \varphi(\omega)$
  - $\Delta \varphi(\omega)$

One array vs Many arrays

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BUSINESS MODEL & EXEC

What we’ve done and where we’re going.
OVERVIEW & FOCUS

How will we make money?

Applications
- Communications
- Sensing

Markets
- 5G Backhaul & Fronthaul
- Fixed wireless access
- 5G Access
- Automotive radar

Revenue streams
- Chip sales
- IP Licenses
- Services

Products
- Full F/E as Chip
- Components as SiP
- Full F/E as SiP

Costs
- Design
- Manufacture
- Sales
- Distribution
**EXECUTION TIMELINE**

- **2014**: Research began
- **2017**: Proof of Concept & Incorporation
- **2018**: Raising funding for product development
- **2020**: First samples delivered to customers
- **2021**: Full scale manufacture
Interested in E-Band F/E for telecommunications. LOI provided. Waiting for samples.

Interested in E-Band BPF (& other F/E components) for single chip CMOS radar. LOI imminent. Waiting for samples.

Interested in ASP for defence (analog FFT). Paying $ 50 k for NRE.

Prospective:
FUNDING TIMELINE

What has been done so far?

Bootstrapped
$ 10 k

2017

GAP ICT & TelAviv SA
Winner
$ 20 k

2018 Q1

SAAB NRE
$ 50 k

2018 Q4

Si Catalyst in-kind
support
$ 1.6 M

2018 Q4

Confirmed - full support!

Almost finalized (term-sheet)

StarFinder & Vigo Systems
$ 1.6 M

2019 Q1
FINANCIALS — MARKET PROJECTIONS (SAM)

- Existing: single link = 10,000 USD
- Multifractal’s disruptive product will bring single link down to 1000 USD
- Drastically raise the volumes shipped. Based on this:
  - our projections indicate a market share of 9.69% in year 4 growing to 15.08% in year 6

<table>
<thead>
<tr>
<th>Year</th>
<th>TAM</th>
<th>CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>$400,000,000.00</td>
<td>38.85%</td>
</tr>
<tr>
<td>2018</td>
<td>$555,400,000.00</td>
<td>38.85%</td>
</tr>
<tr>
<td>2019</td>
<td>$771,172,900.00</td>
<td>38.85%</td>
</tr>
<tr>
<td>2020</td>
<td>$1,070,773,571.65</td>
<td>38.85%</td>
</tr>
<tr>
<td>2021</td>
<td>$1,486,769,104.24</td>
<td>38.85%</td>
</tr>
<tr>
<td>2022</td>
<td>$2,064,378,901.23</td>
<td>38.85%</td>
</tr>
<tr>
<td>2023</td>
<td>$2,866,390,104.36</td>
<td>38.85%</td>
</tr>
</tbody>
</table>

Top Millimeter Wave Equipment Vendors by 1H13 Global Revenue Share
## FINANCIALS — EXPECTED REVENUE (SOM)

<table>
<thead>
<tr>
<th>Theme</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6</th>
<th>Year 7</th>
<th>Year 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. Lean development</td>
<td>2. Production ramp-up</td>
<td>3. Full - Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Objectives</td>
<td>1.1. Develop tech</td>
<td>2.1. Develop product</td>
<td>3.1. Grow market share</td>
<td>1.2. Develop market</td>
<td>2.2. Develop sales and distribution channels</td>
<td>3.2. Grow product line</td>
<td>1.3. Produce and distribute samples</td>
<td>2.3. Full wafer production</td>
</tr>
<tr>
<td>Revenue</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$7,360,000</td>
<td>$19,200,000</td>
<td>$28,400,000</td>
<td>$33,950,000</td>
<td>$47,700,000</td>
</tr>
<tr>
<td>Costs</td>
<td>$555,579</td>
<td>$538,678</td>
<td>$514,646</td>
<td>$5,349,016</td>
<td>$8,064,634</td>
<td>$12,678,928</td>
<td>$15,063,663</td>
<td>$17,675,697</td>
</tr>
<tr>
<td>Profit</td>
<td>-$555,579</td>
<td>-$538,678</td>
<td>-$514,646</td>
<td>$2,010,984</td>
<td>$11,135,366</td>
<td>$15,721,072</td>
<td>$18,886,337</td>
<td>$30,024,303</td>
</tr>
<tr>
<td>Cashflow</td>
<td>$1,053,324</td>
<td>$514,646</td>
<td>$4,895,057</td>
<td>$6,906,041</td>
<td>$18,041,406</td>
<td>$33,762,478</td>
<td>$52,648,815</td>
<td>$82,673,118</td>
</tr>
<tr>
<td>Investment</td>
<td>$1,608,903</td>
<td>$4,895,057</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Tech development funding - $1.6 M
- Commercialization grant - $5 M
QUARTERLY BUDGET

COMPARISON

With Si Catalyst support

- Project Development: 77%
- Salaries: 91%
- Travel: 6%
- Measurements: 3%

Required minimum cash funding: ~ $1M

Without Si Catalyst support

- Project Development: 88%
- Salaries: 31%
- EDA: 45%
- Prototyping: 13%

Required minimum cash funding: ~ $2.65M

Si Catalyst LLC equivalent necessary cash support: ~ $1.6M

We had an offer in the past to this effect; i.e., it is possible

Assuming 80% discount for Synopsys/Cadence & 60% discount for Keysight ADS

EDA cost > $1M

Mostly salary & office space

Mostly EDA, prototyping & salaries

Salaries ~$720k

Prototyping + measurement ~$600k

Office space ~$100k

$1M

$2.65M
IP STRATEGY

IP has been licensed from the University of Pretoria – exclusive lic.

BPF → UK Provisional Patent Application 1720870.3
PCT to be filed

CCHI → PCT filed – PCT/IB/2018/058805

All-pass → PCT filed – PCT/IB/2018/058738

To licence or not licence? That is the question.

• New IP to be developed in the future addressing shortcoming of previous generation implementations
• Freedom to Operate as this will be novel IP

Patent: countries to be filed in, in this order:

- UK
- EU
- Japan
- South Korea
- India
- China
TEAM INTRODUCTION

Dr Piotr Osuch
CTO & Co-founder

Nish Singh
COO & Co-founder

Hendrik Nel
RFIC engineer

Dr Tinus Stander
Tech. Advisor

Dinesh Maheshwari
Biz. Advisor

CA, USA

- CTO: Memory Division, Cypress Semiconductor
- Board of Directors at JEDEC, UPA; Advisory Board at Kandou Bus, Deca Technologies, Zeno Semiconductor, Tutenna.
- Technologist at Silicon Light Machines, Synopsys, Mentor Graphics, Cadence, Microprocessors & Controls LLC
- ~30 years of Technology, Market and Business strategy in Semiconductors, Systems and Software
We look forward to forming a partnership

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Pretoria, South Africa

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APPENDIX — POTENTIAL COMPETITORS
POTENTIAL COMPETITORS (automotive)

Texas Instruments

AWR1243

- AWR1243 - 76-to-81GHz high-performance automotive MMIC
- RF (chirp) bandwidth = 4 GHz → range resolution ~ 4.5 cm
- Cross-range resolution @ max range ~ 70 cm
- IF bandwidth = 5 MHz → ~1-40 ms per computation cycle (refresh rate)
- Cost: $36 per IC, power: a few W.
- Requirement: powerful DSP for 2D-FFT (range-Doppler): for each TxRx pair! Recommended TI C66x:
  - ~ 20 W per core to do 64 point FFT in 1 μs (1.4 GHz)
  - A few cores will be required:
    - 8 cores: → 140 W – 160 W
    - 16 cores: → 320 W
  - Few thousand $ (ADC+DSP+etc.) ~ $3k

Multifractal’s technology will improve on this significantly / add value
✓ TI can be a potential partner or even customer

See next slides for details ...
A pre-select filter will be required - because in future, E-band will be busy! (e.g. telecoms signals). Otherwise, out-of-band signals will mix in-band. The filter should be after LNA & before MIX, as shown (yellow), for full benefit.

versus

Multifractal's IC

No IMA (or greatly reduced!)

Multifractal's IC

Much less powerful DSP required – only to process result – no FFT computation
# Potential Competitors (automotive)

## Texas Instruments

**AWR1243**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TI's AWR1243</th>
<th>Multifractal’s IC</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&gt; 100 W (incl. DSP)</td>
<td>&lt; 20 W (incl. DSP)</td>
<td>5-10X reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Thousands $</td>
<td>Hundreds of $</td>
<td>100X reduction</td>
</tr>
<tr>
<td>Processing speed</td>
<td>&gt; 1 µs per FFT</td>
<td>&lt; 50 ns per FFT</td>
<td>50X improvement (faster multiple object detection)</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>5 MHz</td>
<td>1-4 GHz</td>
<td>100X faster (faster object detection)</td>
</tr>
<tr>
<td>RF bandwidth</td>
<td>4 GHz</td>
<td>4 – 8 GHz</td>
<td>2X larger ➔ 2X resolution (4.5cm ➔ 2.25 cm)</td>
</tr>
<tr>
<td>Complexity</td>
<td>Final system design = complex IMA</td>
<td>Final system design = simple/no IMA!</td>
<td>Supports mass production, lower production costs</td>
</tr>
</tbody>
</table>
Tusk IC NV (Antwerp, Belgium)

- Founded in January 2018 as a spin-off from the KU Leuven ESAT-MICAS research group
- Technology (40 nm CMOS) - [Link]
  - A Push-Pull Complementary mm-Wave Power Amplifier
  - Waveguide receiver
  - ~0.5 THz signal generators (also in 28nm CMOS)
  - 60 GHz outphasing transmitter (PA with high efficiency)
  - 120 GHz quadrature frequency generator (45 LP CMOS)
  - 118 GHz VCO (65nm CMOS)
  - 200 GHz downconverter (90nm CMOS)

Tusk IC value add is mainly in VCOs and signal generation:

- MACOM VCOs $\rightarrow$ ~15 GHz
- ANALOG VCOs $\rightarrow$ ~27 GHz
- Texas Instruments VCOs $\rightarrow$ ~20 GHz

Not part of Multifractal’s value proposition (BPF & ASP)

∴ Tusk IC could be a potential partner or even customer
### POTENTIAL COMPETITORS (telecoms)

**Anokiwave (CA, USA)**

- Founded in 1999
- Technology – [link](#)

<table>
<thead>
<tr>
<th>Market</th>
<th>Band</th>
<th>Product Family</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5G Communications</td>
<td>24/26 GHz</td>
<td>Silicon Core IC</td>
<td>5G Tx/Rx Quad Core IC</td>
</tr>
<tr>
<td></td>
<td>28 GHz</td>
<td>Silicon Core IC</td>
<td>5G Tx/Rx Quad Core IC</td>
</tr>
<tr>
<td></td>
<td>37/39 GHz</td>
<td>Silicon Core IC</td>
<td>5G Tx Quad Core IC</td>
</tr>
<tr>
<td>Active Antenna Innovator Kits</td>
<td>24/26 GHz</td>
<td>Active Antenna</td>
<td>256 Element Innovator Kit</td>
</tr>
<tr>
<td></td>
<td>28 GHz</td>
<td>Active Antenna</td>
<td>256 Element Innovator Kit</td>
</tr>
<tr>
<td>RADAR and Communications</td>
<td>X-Band</td>
<td>Silicon Core IC</td>
<td>Dual Beam Low NF Tx/Rx Quad Core IC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RF Front End IC</td>
<td>Medium Power Front End MMIC</td>
</tr>
<tr>
<td>Active Antennas</td>
<td>K-Band</td>
<td>Silicon Core IC</td>
<td>4-element Dual Pol Rx-Quad Core IC</td>
</tr>
<tr>
<td></td>
<td>Ka-Band</td>
<td>Silicon Core IC</td>
<td>4-element Dual Pol Tx Quad Core IC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PA IC</td>
<td>3W High Power Amplifier MMIC</td>
</tr>
<tr>
<td>SATCOM Active Antennas</td>
<td>K-Band</td>
<td>Silicon Core IC</td>
<td>Intelligent Gain Block IC w/ SW</td>
</tr>
<tr>
<td></td>
<td>Ka-Band</td>
<td>Silicon Core IC</td>
<td>Intelligent Gain Block IC w/o SW</td>
</tr>
<tr>
<td>Multi-Market</td>
<td>Ku-Band</td>
<td>Silicon Core IC</td>
<td>Intelligent Gain Block IC w/ SW</td>
</tr>
<tr>
<td></td>
<td>Ka-Band</td>
<td>Silicon Core IC</td>
<td>Intelligent Gain Block IC w/o SW</td>
</tr>
<tr>
<td>Point-to-Point Radio</td>
<td>E-Band</td>
<td>LNA IC</td>
<td>Low Noise Amplifier MMIC</td>
</tr>
</tbody>
</table>

Anokiwave’s primary value add is in tunable AMPS and Phase Shifters (X, Ku, K, Ka).

At E-band they have a tunable AMP

![Diagram](image)

**Summary**

Not part of Multifractal’s value proposition (BPF & ASP)

◆ Anokiwave is most probably a future partner
POTENTIAL COMPETITORS (telecoms)

Other interesting research

- mmWave Circulator IC
  - Columbia Engineering researchers in collaboration with UT-Austin
  - First magnet-free non-reciprocal circulator on a silicon
  - Value proposition: saving real-estate and costs for full-duplex COM Ics
  - Early-stage research (many performance metrics unknown)
  - Existing competitors: none on-chip. There are some products in waveguide such as smiths interconnect.
  - Existing technology uses switches for full-duplex – similar to what they do.
- What does this mean for Multifractal:
  - Not part of our value proposition
  - If they commercialize they could become potential partners
  - ... or we could commercialize similar tech before them
APPENDIX — HIGH-LEVEL END-PRODUCT SPECIFICATIONS
## LINK BUDGET (telecoms)

**Low-level requirements**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency (GHz)</td>
<td>73.50</td>
</tr>
<tr>
<td>PA output power (dBm)</td>
<td>20.00</td>
</tr>
<tr>
<td>Number of PAS</td>
<td>32.00</td>
</tr>
<tr>
<td><strong>Total output power (dBm)</strong></td>
<td><strong>35.05</strong></td>
</tr>
<tr>
<td>Number of Tx antenna elements</td>
<td>64.00</td>
</tr>
<tr>
<td>Tx antenna element gain (dB)</td>
<td>10.00</td>
</tr>
<tr>
<td>Antenna &amp; feed network loss (dB)</td>
<td>4.00</td>
</tr>
<tr>
<td><strong>Total Tx antenna array gain (dB)</strong></td>
<td><strong>24.06</strong></td>
</tr>
<tr>
<td>EIRP (dBm)</td>
<td>59.11</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>300.00</td>
</tr>
<tr>
<td>Att no rain (dB/km)</td>
<td>0.50</td>
</tr>
<tr>
<td>Att rain 5mm/h (dB/km)</td>
<td>3.00</td>
</tr>
<tr>
<td>Att rain 25mm/h (dB/km)</td>
<td>10.00</td>
</tr>
<tr>
<td>Att rain 150mm/h (dB/km)</td>
<td>40.00</td>
</tr>
<tr>
<td>Att no rain (dB)</td>
<td>0.15</td>
</tr>
<tr>
<td>Free space loss</td>
<td>119.31</td>
</tr>
<tr>
<td>Path loss (urban)</td>
<td>144.33</td>
</tr>
<tr>
<td><strong>Total Path loss (dB) (no rain)</strong></td>
<td><strong>144.48</strong></td>
</tr>
<tr>
<td><strong>Total Path loss (dB) (light rain)</strong></td>
<td><strong>145.23</strong></td>
</tr>
<tr>
<td><strong>Total Path loss (dB) (heavy rain)</strong></td>
<td><strong>156.33</strong></td>
</tr>
</tbody>
</table>

**Technical specification**

- **Multifractal's front-end (gen 1)**
  - Tx power: >35 dBm
  - Tx antenna array: 8x8 or more
  - EIRP: > 60 dBm
  - Range: <300 m
  - Gain: 85-100 dB
  - Channel bandwidth: 2 GHz (5 GHz potentially)
  - Rx elements: 8x8 or more
  - Total Rx antenna gain: >25 dBi
  - NF: <5 dB
  - P1dB: > 20 dBm
  - IP3: > 25 dBm

### Key Performance Metrics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Received power norm (dBm)</strong></td>
<td>-85.37</td>
</tr>
<tr>
<td><strong>Received power worst (dBm)</strong></td>
<td>-97.22</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>2000.00</td>
</tr>
<tr>
<td>Operating temperature (celsius)</td>
<td>100.00</td>
</tr>
<tr>
<td>Thermal noise floor (dBm)</td>
<td>-79.87</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>5.00</td>
</tr>
<tr>
<td>SNR (dB) per Rx antenna element</td>
<td>-10.50</td>
</tr>
<tr>
<td>Number of Rx antenna element</td>
<td>64.00</td>
</tr>
<tr>
<td>Rx antenna element gain (dB)</td>
<td>10.00</td>
</tr>
<tr>
<td>Rx antenna feed network loss (dB)</td>
<td>3.50</td>
</tr>
<tr>
<td><strong>Total Rx antenna array gain (dB)</strong></td>
<td><strong>24.56</strong></td>
</tr>
<tr>
<td>SNR after beamforming (norm) (dB)</td>
<td>14.07</td>
</tr>
<tr>
<td>SNR after beamforming (worst) (dB)</td>
<td>2.22</td>
</tr>
<tr>
<td>Signal power - S (W)</td>
<td>8.30E-10</td>
</tr>
<tr>
<td>Signal power worst - S (W)</td>
<td>5.42E-11</td>
</tr>
<tr>
<td>Noise power - N (W)</td>
<td>3.26E-12</td>
</tr>
<tr>
<td>Eb/no (QPSK) - dB</td>
<td>5.00</td>
</tr>
<tr>
<td>BER</td>
<td>5.95E-03</td>
</tr>
<tr>
<td><strong>Rb (max bit rate no rain) (gbps)</strong></td>
<td><strong>161.27</strong></td>
</tr>
<tr>
<td><strong>Rb (max bit rate heavy rain) (gbps)</strong></td>
<td><strong>10.53</strong></td>
</tr>
<tr>
<td><strong>Signal power - S (W) (max bit rate heavy rain)</strong></td>
<td><strong>5.42E-11</strong></td>
</tr>
</tbody>
</table>

---

# Generation 1 Front-End (Telecoms)

## High-level specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multifractal’s gen 1 front-end</th>
<th>Siklu E-band front-end (EtherHaul 8010FX)</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&lt; 2 W</td>
<td>50 W (including DSP)</td>
<td>10-20X power reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Tens of $</td>
<td>~$ 11k</td>
<td>&gt;100X cost reduction</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>5 GHz</td>
<td>2 GHz</td>
<td>SoC solution – fewer components, higher bandwidth, lower power</td>
</tr>
<tr>
<td>Throughput</td>
<td>10 Gbps full duplex</td>
<td>10 Gbps full duplex (FDD)</td>
<td>-</td>
</tr>
<tr>
<td>RF bands</td>
<td>71-76, 81-86 GHz</td>
<td>71-76, 81-86 GHz</td>
<td>-</td>
</tr>
<tr>
<td>System gain</td>
<td>80 – 98 dB</td>
<td>64 – 93 dB</td>
<td>-</td>
</tr>
<tr>
<td>Range</td>
<td>300 m</td>
<td>2.73 – 3.7 km</td>
<td>Small cell densification</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-45 to +85°C ++</td>
<td>-45 to +55°C</td>
<td>Single chip solution – better temperature performance / match</td>
</tr>
<tr>
<td>Dimensions</td>
<td>~ 10 by 10 cm (with MIMO array) – RF module (~5x5 cm)</td>
<td>~ 30 by 30 cm (single antenna – no MIMO)</td>
<td>Massive MIMO</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 100 g</td>
<td>~ 5 kg</td>
<td>Small, lightweight</td>
</tr>
<tr>
<td>NF</td>
<td>~5 dB</td>
<td>?</td>
<td>Relaxed requirements due to small cell dens.</td>
</tr>
</tbody>
</table>

Smaller range has benefits – our solution allows for this small cell dens. due to lower costs, power and size.
# Generation 2 Front-end (telecoms)

High-level specifications (ASP only – cognitive radio – other specs stay the same)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multifractal’s IC</th>
<th>TI’s AWR1243 / DSP 66x series or equivalent</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&lt; 20 W (incl. DSP)</td>
<td>&gt; 100 W (incl. DSP)</td>
<td>5-10X reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Hundreds of $</td>
<td>Thousands $</td>
<td>&gt;100X reduction</td>
</tr>
<tr>
<td>Processing speed</td>
<td>&lt; 50 ns per FFT</td>
<td>&gt; 1 μs per FFT (1 core)</td>
<td>50X improvement (faster multiple object detection)</td>
</tr>
<tr>
<td>IF bandwidth (automotive radar)</td>
<td>1-4 GHz</td>
<td>5 MHz</td>
<td>100X faster (faster detection)</td>
</tr>
<tr>
<td>RF bandwidth (automotive radar)</td>
<td>4 – 8 GHz</td>
<td>4 GHz</td>
<td>2X larger → 2X resolution (4.5cm → 2.25 cm)</td>
</tr>
<tr>
<td>Complexity</td>
<td>Final system design = simple/no IMA</td>
<td>Final system design = complex IMA</td>
<td>Supports mass production, lower production costs</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>50 dB</td>
<td>~50 dB</td>
<td></td>
</tr>
<tr>
<td>ENOB</td>
<td>4</td>
<td>8</td>
<td>Relaxed ADC requirements</td>
</tr>
<tr>
<td>Equivalent n-points</td>
<td>70 (current technology with the aim to improve)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power accuracy</td>
<td>±3 dB</td>
<td>~ 1 dB</td>
<td></td>
</tr>
<tr>
<td>Frequency accuracy</td>
<td>~ 100 Mhz</td>
<td>~ 100 MHz</td>
<td></td>
</tr>
<tr>
<td>Magnitude / phase information</td>
<td>Magnitude only</td>
<td>Both</td>
<td>Application dependent</td>
</tr>
</tbody>
</table>

Existing solution do not scale well with bandwidth

**TI 66x (8 cores)**

![Graph showing baseline, activity, and total power vs. clock frequency.](chart.png)

- Baseline
- Activity
- Total
**GENERATION 2 FRONT-END** (telecoms)

High-level specifications (ASP only – frequency beam steering – other specs stay the same)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multifractal’s IC</th>
<th>TI’s AWR1243 / DSP 66x series or equivalent</th>
<th>Our value add</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>&lt; 20 W (incl. DSP)</td>
<td>&gt; 100 W (incl. DSP)</td>
<td>5-10X reduction</td>
</tr>
<tr>
<td>Cost</td>
<td>Hundreds of $</td>
<td>Thousands $</td>
<td>10X reduction</td>
</tr>
<tr>
<td>Processing speed (tracking speed)</td>
<td>&lt; 50 ns per operation</td>
<td>&gt; 1 µs per operation (1 core)</td>
<td>50X improvement (faster steering)</td>
</tr>
<tr>
<td>Complexity</td>
<td>Final system design = simple/no IMA!</td>
<td>Final system design = complex IMA</td>
<td>Supports mass production, lower production costs</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>50 dB</td>
<td>~50 dB</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt; 8GHz</td>
<td>4 GHz is already a challenge</td>
<td></td>
</tr>
<tr>
<td>Channels per antenna (frequency mapped to angles)</td>
<td>&gt; 30 (only one array! – one tile)</td>
<td>? (Unheard of) – many tiles / antenna arrays needed</td>
<td>More massive MIMO! Truly big data.</td>
</tr>
<tr>
<td>Frequency reconfigurability (lens effect)</td>
<td>8 GHz band → 100 MHz band</td>
<td>Unheard of</td>
<td>Frequency lensing</td>
</tr>
</tbody>
</table>

10X improvement (faster steering)
APPENDIX - TECHNOLOGY OVERVIEW
TECHNOLOGY OVERVIEW

1. Fully tunable, active, enhanced, high Q-factor mm-wave resonators

- Resonator is the building block of the BPF. Nobody in industry has integrated BPF on Silicon due to low $Q_0$-factors.

- Silicon-proven in 130nm BiCMOS GF US 8HP with HBT $f_T/f_{MAX}$ 260/320 GHz

- SOTA $Q_0$ of ~10, Our $Q_0$ of ~1000

- Can be scaled for other mmWave frequencies and processes (XXnm, CMOS, SOI, BiCMOS)

- E-band (71-76 and 81-86 GHz)

- Centre frequency and Q-factor tunable post-production with control voltages

First-ever on-chip mm-wave microstrip resonators with $Q > 100$
## TECHNOLOGY OVERVIEW

1. Fully tunable, active, enhanced, high Q-factor mm-wave resonators

<table>
<thead>
<tr>
<th>f₀ (GHz)</th>
<th>FBW</th>
<th>Process</th>
<th>IL (dB)</th>
<th>Q-factor</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>&lt; 10%</td>
<td>0.13 μm SiGe BiCMOS</td>
<td>&lt; 0.1</td>
<td>&gt; 1500</td>
<td>This work</td>
</tr>
<tr>
<td>77</td>
<td>15.5%</td>
<td>0.14 μm SiGe BiCMOS</td>
<td>6.4</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>11.7%</td>
<td>0.13 μm standard CMOS</td>
<td>3.9</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>28.6%</td>
<td>0.18 μm standard CMOS</td>
<td>3.8</td>
<td>[3]</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>25.7%</td>
<td>0.18 μm standard CMOS</td>
<td>3.6</td>
<td>[4]</td>
<td></td>
</tr>
<tr>
<td>65.0</td>
<td>3.23%</td>
<td>0.15 μm GaAs</td>
<td>2.8</td>
<td>&lt; 100</td>
<td>[6]</td>
</tr>
<tr>
<td>65.0</td>
<td>4.00%</td>
<td>0.15 μm GaAs</td>
<td>3.0</td>
<td>[6]</td>
<td></td>
</tr>
<tr>
<td>22.7</td>
<td>7.39%</td>
<td>0.18 μm CMOS</td>
<td>0.15</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>6.45</td>
<td>17.05%</td>
<td>2.00 μm GaAs</td>
<td>0.25 gain</td>
<td>[8]</td>
<td></td>
</tr>
</tbody>
</table>

TECHNOLOGY OVERVIEW

2. Tunable active second-order all-pass network (CMOS)

- Second-order all-pass network - building block of any ASP
- SOTA all-pass network - bulky soft-substrate passive microstrip
- Multifractal - first-ever active on-chip second-order all-pass network with delay Q-value larger than 1
- Low insertion loss ripple ( < 3.1 dB)
- Bandwidth of 280 MHz in 0.35 um CMOS
- 0.0625 mm² real-estate
- Reduced sensitivity to process tolerances
- Prototyped in 0.35 um CMOS and measured

100 microns

Second-order all-pass network – micrograph

Second-order all-pass network – measurement setup

PCT filed – PCT/IB/2018/058738
2. Tunable active second-order all-pass network (CMOS)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>ORDER</th>
<th>Q_0</th>
<th>f_0 (GHz)</th>
<th>3dB Bandwidth (GHz)</th>
<th>Technology</th>
<th># of L</th>
<th>Size (mm^2)</th>
<th>Power (mW)</th>
<th>Magnitude variation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>2nd</td>
<td>1.15</td>
<td>0.07</td>
<td>0.280</td>
<td>0.35 µm CMOS</td>
<td>0</td>
<td>0.0625</td>
<td>15 (excl. DAC)</td>
<td>3.1</td>
</tr>
<tr>
<td>[1]</td>
<td>2nd</td>
<td>0.19 (0.59)**</td>
<td>3</td>
<td>4</td>
<td>0.25 µm CMOS</td>
<td>0</td>
<td>0.085</td>
<td>&lt; 95</td>
<td>1.5 (&gt; 25)</td>
</tr>
<tr>
<td>[2]</td>
<td>2nd</td>
<td>0.04 (0.52)</td>
<td>7</td>
<td>13</td>
<td>0.13 µm CMOS</td>
<td>1</td>
<td>0.0627</td>
<td>18.5</td>
<td>0.4 (&gt; 13)</td>
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<tr>
<td>[3]</td>
<td>2nd</td>
<td>0.098</td>
<td>7</td>
<td>16.5</td>
<td>0.09 µm CMOS</td>
<td>0</td>
<td>-</td>
<td>&lt; 27</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>[4]</td>
<td>2nd</td>
<td>0.049 (0.81)</td>
<td>6.3</td>
<td>12</td>
<td>0.13 µm CMOS</td>
<td>1</td>
<td>-</td>
<td>16.5</td>
<td>- 1.5 (&gt; 10)</td>
</tr>
<tr>
<td>[5]</td>
<td>2nd</td>
<td>0.047</td>
<td>6</td>
<td>7.5</td>
<td>SiGe BICMOS HBT</td>
<td>1</td>
<td>0.49°</td>
<td>121</td>
<td>- 1</td>
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<tr>
<td>[6]</td>
<td>2nd (f_0 = 0)’</td>
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<td>0</td>
<td>12.2</td>
<td>0.16 µm CMOS</td>
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<td>0.15</td>
<td>90</td>
<td>1.4</td>
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<td>[7]</td>
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<td>0</td>
<td>10</td>
<td>SiGeRF HBT</td>
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<td>0.4197</td>
<td>38.8</td>
<td>2 – 2.5</td>
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<td>0</td>
<td>0</td>
<td>4.38</td>
<td>0.18 µm CMOS</td>
<td>0</td>
<td>0.0512</td>
<td>7.88</td>
<td>-</td>
</tr>
<tr>
<td>[9]</td>
<td>2nd (f_0 = 0)’</td>
<td>0</td>
<td>0</td>
<td>&gt; 3</td>
<td>0.13 µm CMOS</td>
<td>0</td>
<td>0.29</td>
<td>112</td>
<td>- 0.75</td>
</tr>
</tbody>
</table>

* Including pads, ** constant delay with frequency, *** values in brackets are computed over the entire bandwidth with the associated magnitude variation also shown in brackets.

References:
TECHNOLOGY OVERVIEW

3. Mm-wave active second-order all-pass network (BiCMOS)

- First mm-wave second-order all-pass network: 10 GHz linear group delay bandwidth
- Prototype - 130 nm BiCMOS
- Power - 20 mW
- Size - 0.09 mm²
- Average output noise of 0.69 nV/√Hz
- Prototyped, measurements pending

Prototype – 130 nm BiCMOS

Power – 20 mW

Size – 0.09 mm²

Average output noise of 0.69 nV/√Hz

Prototyped, measurements pending

Mm-wave bandwidth CCII – micrograph

Mm-wave bandwidth CCII – simulated results
TECHNOLOGY OVERVIEW

3. Mm-wave active second-order all-pass network (BiCMOS)

| \( Q_0 \) | \( f_0 \) (GHz) | -3dB (GHz) | Technology | Size (mm\(^2\)) | Power (mW) | \( \Delta |T| \) (dB) |
|---|---|---|---|---|---|---|
| [1] | 3.6 | 36 | 40 | 0.13 \( \mu \)m SiGe | 0.0625 | 9.3 | 1.4 |
| [4] | 0° | 0 | 12.2 | 0.16 \( \mu \)m CMOS | 0.07 | 90 | \( \sim \) 1.4 |
| [5] | 0° | 0 | 4.38 | 0.18 \( \mu \)m CMOS | 0.0512 | 7.88 | - |
| [7] | 0.19 | 3 | 4 | 0.25 \( \mu \)m CMOS | 0.085 | \( < 95 \) | \( \sim \) 1.5 |
| [8] | 0.04 | 7 | 13 | 0.13 \( \mu \)m CMOS | 0.0627 | 18.5 | \( \sim \) 0.5 |
| [9] | 0.098 | 7 | 16.5 | 0.09 \( \mu \)m CMOS | - | \( < 27 \) | < 1 |
| [10] | 0.049 | 6.3 | 12 | 0.13 \( \mu \)m CMOS | - | 16.5 | \( \sim \) 1.5 |
| [11] | 0.047 | 6 | 7.5 | 0.25 \( \mu \)m SiGe | 0.49\* | 121 | \( \sim \) 1 |

*This work. Cascaded two first-order sections (no complex pole/zero). \( ^* \)Including pads. \( ^{**} \)\( |T| \) represents either a power or voltage transfer function.

4. High-precision CMOS CCII with stability and peaking control

A CCII is a versatile analogue building block (of e.g. all-pass networks)

- Large bandwidths (800 MHz – 350 nm CMOS)
- High accuracy (feedback mechanism) - voltage and current following to within 0.5 %
- Stability of the feedback loop (post-production tunable phase margin)
- Post-production peaking control (reduce ripple) to account for process tolerances
- Prototyped and measured:
  - Power – 5 mW
  - Size – 0.023 mm²

CCII+ – measurement setup

CCII+ – micrograph

CCII+ – measurement

Manufactured using:
PCT filed – PCT/IB/2018/058805
# TECHNOLOGY OVERVIEW

4. High-precision CMOS CCII with stability and peaking control

<table>
<thead>
<tr>
<th>Ref.</th>
<th>VOLTAGE GAIN (V)</th>
<th>CURRENT gain (α)</th>
<th>R₁ (Ω)</th>
<th>R₂ (kΩ)</th>
<th>-3dB Bandwidth (MHz)</th>
<th>Technology</th>
<th>Measured Results</th>
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<tr>
<td>This work</td>
<td>1.0115</td>
<td>1.0115</td>
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<td>20</td>
<td>500</td>
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<tr>
<td>[1]</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>~1</td>
<td>off-chip</td>
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<td>[2]</td>
<td>0.9886</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>20</td>
<td>1.2 μm CMOS</td>
<td>No</td>
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<td>[3]</td>
<td>0.99</td>
<td>0.99</td>
<td>2.3</td>
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<td>-</td>
<td>10</td>
<td>0.6 μm CMOS</td>
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<td>[4]</td>
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<td>[5]</td>
<td>-</td>
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<td>~50</td>
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<td>-</td>
<td>700</td>
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<tr>
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<td>0.9999</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
<td>2.16</td>
<td>0.5 μm CMOS</td>
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<tr>
<td>[7]</td>
<td>0.96</td>
<td>0.976</td>
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<td>35</td>
<td>2600</td>
<td>0.35 μm CMOS</td>
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<td>~50</td>
<td>0.35 μm CMOS</td>
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<td>0.9999</td>
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<td>-</td>
<td>-</td>
<td>~400</td>
<td>0.5 μm CMOS</td>
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<tr>
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<td>1.0015</td>
<td>0.003</td>
<td>-</td>
<td>-</td>
<td>~250</td>
<td>1.2 μm CMOS</td>
</tr>
</tbody>
</table>

TECHNOLOGY OVERVIEW

5. Mm-wave bandwidth CCII with peaking reduction (BiCMOS)

- Mm-wave bandwidths (27 GHz) - first time ever.
- Feedback mechanism to improve precision (to within 1%)
- Peaking reduction (reduce passband ripple)
- Prototyped and measured - post-processing pending

First-ever mm-wave bandwidth CCII

150 microns

Know-how, PCT to be filed (potentially)
6. Narrowband coupled resonator bandpass filters

- First narrowband on-chip mmWave BPF (can be scaled to various topologies)
- Fractional bandwidths of 0.5%
- Filters as narrow as 500 MHz
- Applicable to E-Band 71-76 and 81-86 GHz
- Resonator Q enhanced from 10 to 1000.
- Opportunities for extension to a tunable BPF and/or low-noise filtering amplifier
- Second prototype pending - pending funding

Simulation results of the tunable, high-Q mm-wave resonators
An LNA is a key component of any transceiver.

- 56-92 GHz operating range
- 15 GHz bandwidth
- Gain of > 13 dB
- NF < 8 dB
- Complements Multifractal’s technology portfolio enabling a future climb in the value chain
- Noise measurements pending - pending funding

Mm-wave LNA

Manufactured using: GLOBALFOUNDRIES

150 microns