

EUROPEAN MICROWAVE WEEK 2015

SIX DAYS • THREE CONFERENCES • ONE EXHIBITION

PALAIS DES CONGRÈS, PARIS, FRANCE
SEPTEMBER 6 - 11, 2015

Exhibition Opening Hours:

- Tuesday 8th September: 9.30 – 18.00
- Wednesday 9th September: 9.30 – 17.30
- Thursday 10th September: 9.30 – 16.30

Concepts for Highly Integrated Automotive Radar Circuits

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WS12: EuMIC - SiGe for mm-Wave and THz

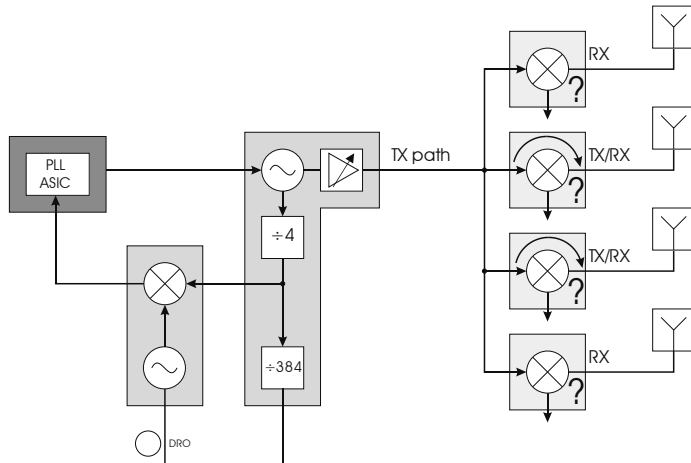


Content – Part I

- A short history of SiGe in automotive radar (AR)
- Upcoming system level requirements
- Concepts to meet those requirements
- Taking a look at radar outside automotive
- The interplay of systems engineering and circuit design

SiGe for mm-Wave and THz

SiGe in AR – the very beginnings

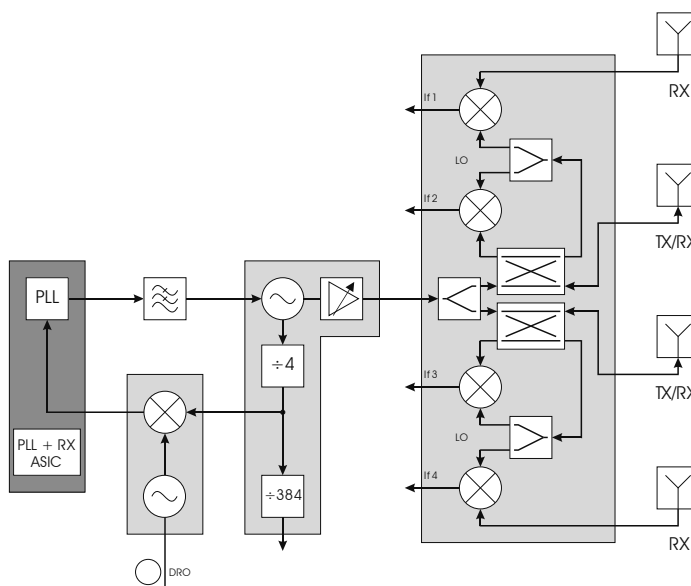


An early draft (ca. 2005)

When SiGe first entered the AR field, it had to compete against systems that were highly fragmented over many individual special-function chips or discrete semiconductors. Our first 'RF system' sketches reflect this mindset ...

SiGe for mm-Wave and THz

SiGe in AR – the very beginnings

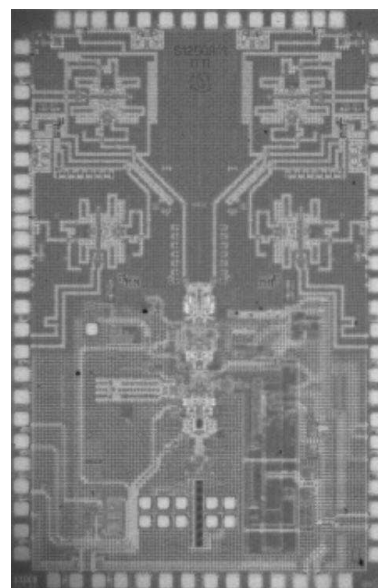
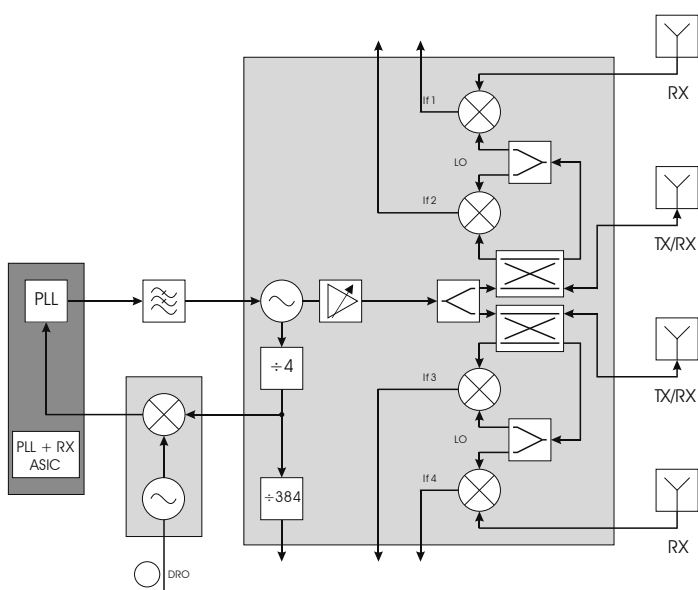


An early draft (ca. 2005)

Looking only at individual performance parameters, SiGe could not directly compete against those special-function chips.

SiGe for mm-Wave and THz

SiGe in AR – the very beginnings



The product

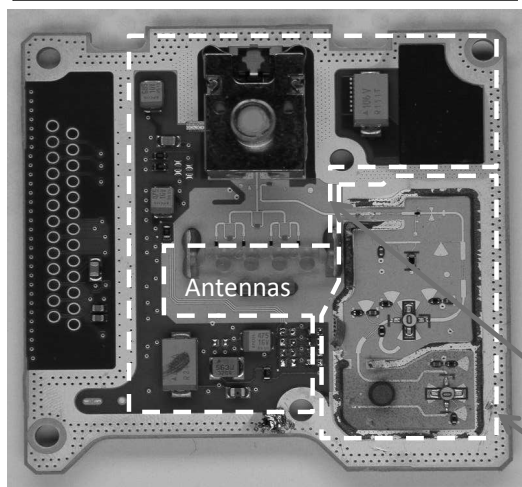
The key to success was **integration**:

When combining multiple function blocks into one single chip, SiGe could leverage a benefit.

SiGe for mm-Wave and THz

GaAs discrete (LRR2) vs. SiGe integrated (LRR3)

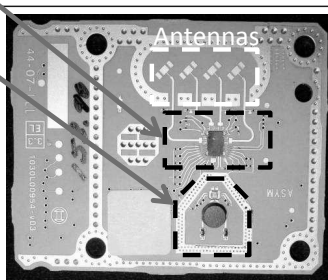
RF-Board 2nd Gen.
62 x 68 mm² (~42 cm²)



GaAs discrete - 2005

		Range	Accuracy
Distance m	LRR2 (GaAs)	2 - 150	0.5
	LRR3 (SiGe)	0.5 - 250	0.1
Relative Velocity m/s	LRR2 (GaAs)	-60 to + 20	±0.25
	LRR3 (SiGe)	-80 to +30	± 0.12
Angle deg°	LRR2 (GaAs)	±8	0.4
	LRR3 (SiGe)	±15	0.1

RF-Board 3rd Gen.
25 x 35 mm² (~9 cm²)



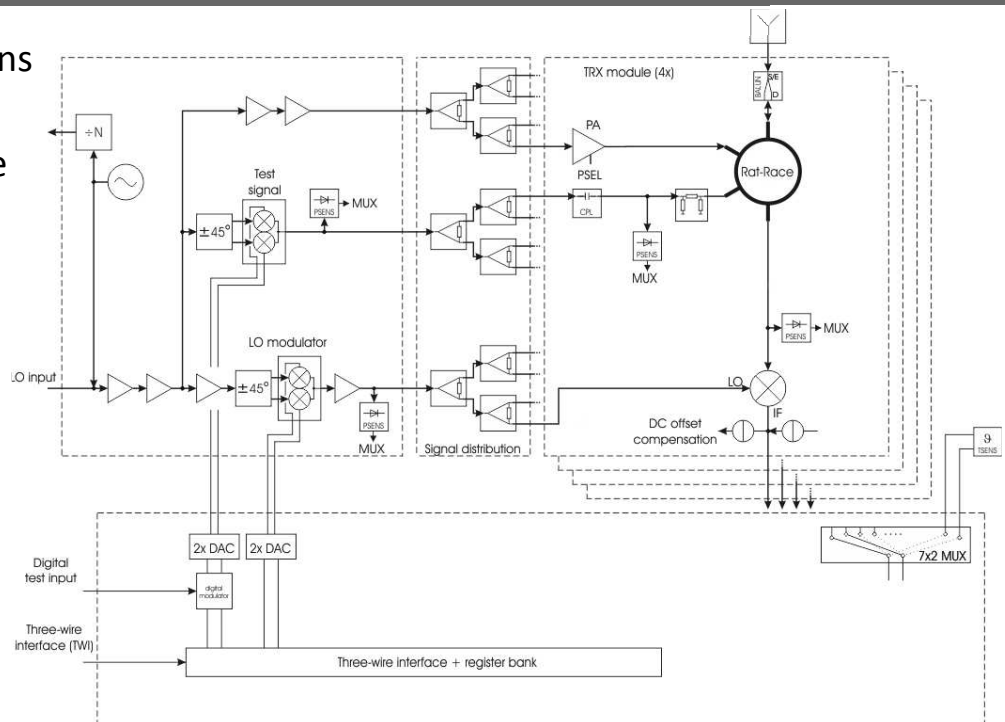
SiGe
2009



SiGe for mm-Wave and THz

Integration in SiGe

- All mm-Wave functions in one chip
- Four transmit/receive (TRX) channels
- Built-in self test; monitoring
- Programmable features through digital interface



Ref. (1)

What are the limits for integration in purely bipolar SiGe?

SiGe for mm-Wave and THz

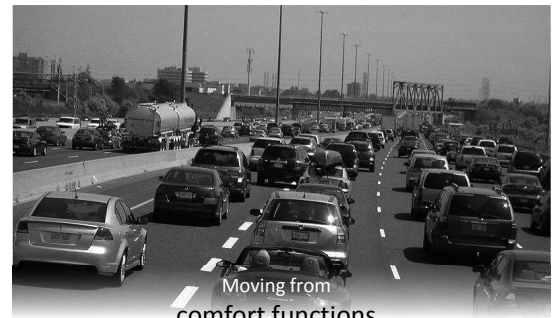
Limitations of pure SiGe bipolar

- **RF** functionality has been demonstrated:
 - + transmit output power
 - + VCO phase noise and tuning bandwidth
 - + receiver noise floor, linearity and conversion gain
 - + Access to relevant parameters to allow ‘health’ monitoring, e.g. power and temperature sensors
 - + Control methods and algorithms can be applied externally (serial interface)
- On the other side:
 - Bipolar transistors are not the first choice for implementing more complex digital functions (circuit size, current consumption, design tools)
 - Higher RF I/O count → larger chip size, PCB fan-out
 - Integrating more functions (e.g., more transmit or receive channels) in this technology will result in too high power dissipation

SiGe for mm-Wave and THz

What comes next?

- In Europe each year about 1.3 million traffic accidents cause:
 - More than 40.000 fatalities
 - Economic damage of more than 200 billion € per year
- Human error is involved in over 90% of accidents
- Automotive radar help drivers to
 - Maintain a safe speed
 - Keep a safe distance
 - Avoid overtaking in critical situations
 - Safely pass intersections
 - Avoid crashes with vulnerable road user
 - Reduce severity of an accident
 - Drive more efficiently



Moving from
comfort functions
(e.g. adaptive cruise control)
in luxury cars

to
safety functions

(e.g., emergency braking, pre-crash preparation)
in every car.

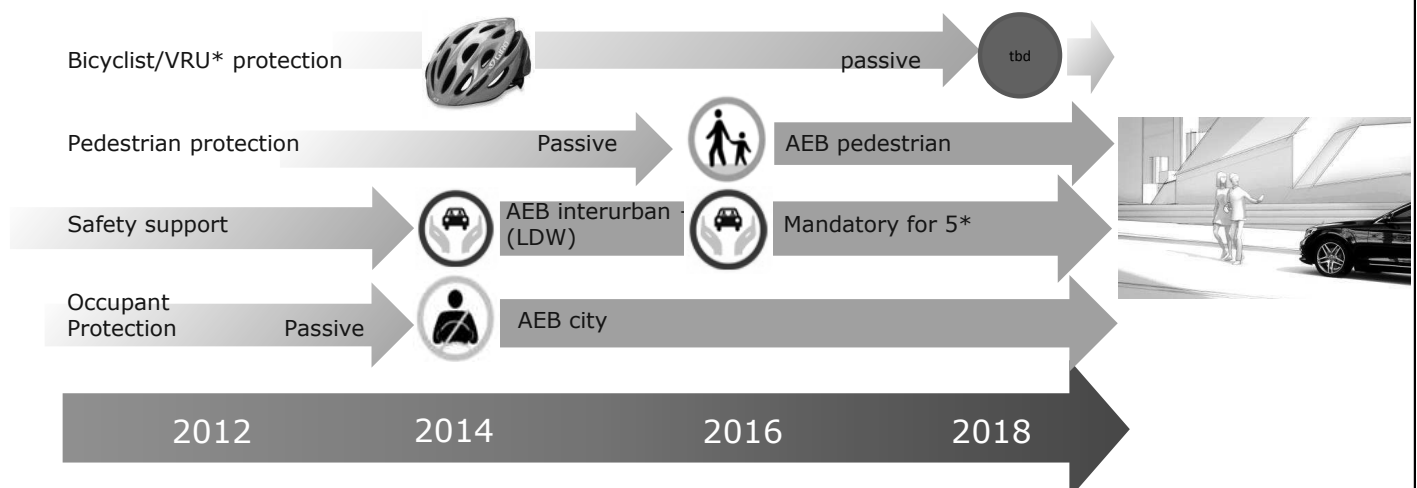


http://en.wikipedia.org/wiki/File:401_Gridlock.jpg

en.wikipedia.org/wiki/Rear-end_collision#mediaviewer/File:Car_accident_-_NSE_Malaysia.jpg

SiGe for mm-Wave and THz

The Safety Market – EuroNCAP* is a strong driver



- European OEMs consider 5 stars a MUST and add required technology to new platforms
- From 2016 onwards, a 5 star rating is not possible without radar/camera
- Radar/camera combination standard equipment for EU cars
- Other regions expected to follow the EU with several years delay (e.g. Korea in 2016)
- From 2018 e.g. cyclist protection is expected raise the bar further

NCAP = New Car Assessment Program
VRU = Vulnerable Road User
AEB = Autonomous Emergency Braking

SiGe for mm-Wave and THz

New applications – new requirements

- Top-level system requirements:
 - High availability – provide an operational system also in adverse conditions
 - High data quality – acquire relevant radar data; identify and avoid false targets
 - Functional safety – Monitor if the system is in nominal condition; quickly detect a faulty function; do not pass on false data
 - Higher resolution – (e.g., pedestrian detection) → bandwidth, number of antennas → MIMO, virtual antennas

SiGe for mm-Wave and THz

New system concepts

- What is different for upcoming system concepts?
 - Available processing power / DSP is growing continuously, new concepts become feasible
 - Digital beamforming (RX), multiple RX channels
 - Virtual antenna arrays, multiple-input, multiple output (MIMO) radar through sophisticated signal processing
 - Very fast ramps, higher sweep bandwidth, signal processing over multiple ramps
 - A great variety of FMCW scenarios, i.e., ramp times and ramp bandwidth, resulting in the requirement for
 - a very flexible IF processing chain (gain steps, high-pass / low-pass corner frequencies, sampling rates)
 - A very agile PLL / frequency ramper and higher bandwidth VCO
 - Different modulation schemes, e.g. BPSK, coded, pseudo-noise ...
 - Integrated support for functional safety: ISO 26262; ASIL levels ...

SiGe for mm-Wave and THz

How can these requirements be met? What does it mean on chip level?

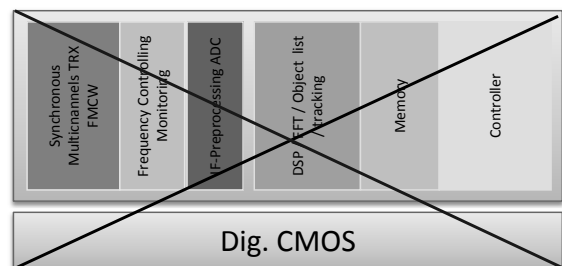
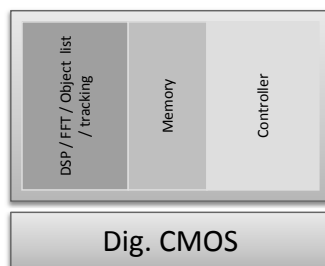
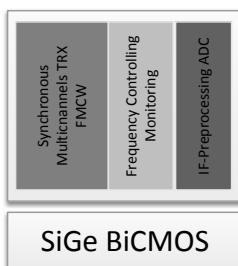
- A larger number of RF channels / functions with higher performance and/or lower power consumption
 - Use a faster SiGe HBT technology, and wisely balance performance vs. power consumption
- Fast, agile and versatile control of many parameters, for example:
 - depending on ramp scenario, boost PLL settling behavior by switching charge pump current and loop filter bandwidth; use two-point modulation
 - Depending on IF bandwidth and signal level, switch gain in RX chain, high-pass and low-pass corner frequencies, data rate
- Design with functional safety in mind, for example
 - Avoid design with hard to detect failure modes
 - Autonomous detection of abnormal circuit function or unusual conditions, and
 - Raise an alarm to allow the sensor to enter a safe state

These requirements can only be met with a faster SiGe HBT, combined with a fully capable CMOS technology.

Bringing this complexity on a chip (SoC) also requires new methodology in concept and circuit design.

SiGe for mm-Wave and THz

Why Next Gen in BiCMOS? System Partitioning!



- | | |
|---|--|
| <ul style="list-style-type: none"> + Optimum technologies for RF / analog / mixed signal and digital functions + High performance SiGe ($f_{\max}=400$ GHz) for lowest power consumption, phase noise, highest linearity and output power + High performance MC can utilize most advanced digital CMOS + Optimized and stable RF/AMS section for use with scalable MC solution + Optimized cost / performance trade-off | <ul style="list-style-type: none"> – Inferior performance of RF/AMS section if implemented in advanced digital CMOS – MC would always lag behind state-of-the-art as development cycles with RF/AMS included take much longer time – Waste of expensive CMOS area for non-shrinkable analog functions – Up-scaling to higher channel count by employment of multiple single chip units not cost-efficient (redundant MCs) or even not possible |
|---|--|

SiGe for mm-Wave and THz

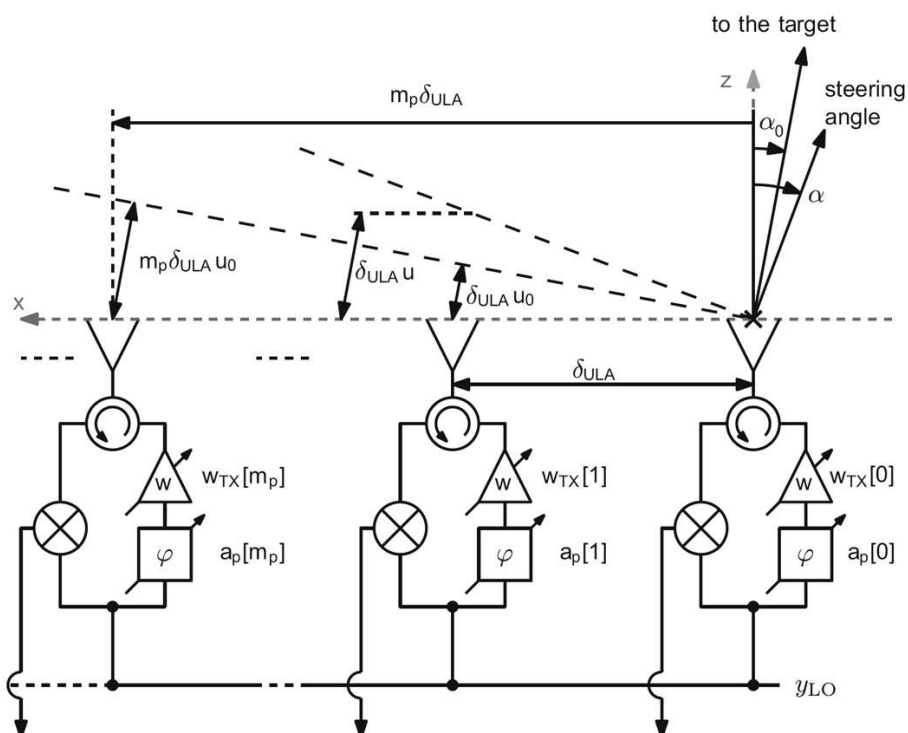
Concepts

- Digital beamforming (RX beamforming) and phased-array antennas (TX beamforming)
- Virtual antenna arrays
- Fast and flexible FMCW ramp generation
- A highly flexible RX chain

SiGe for mm-Wave and THz

Digital beamforming (TX and RX)

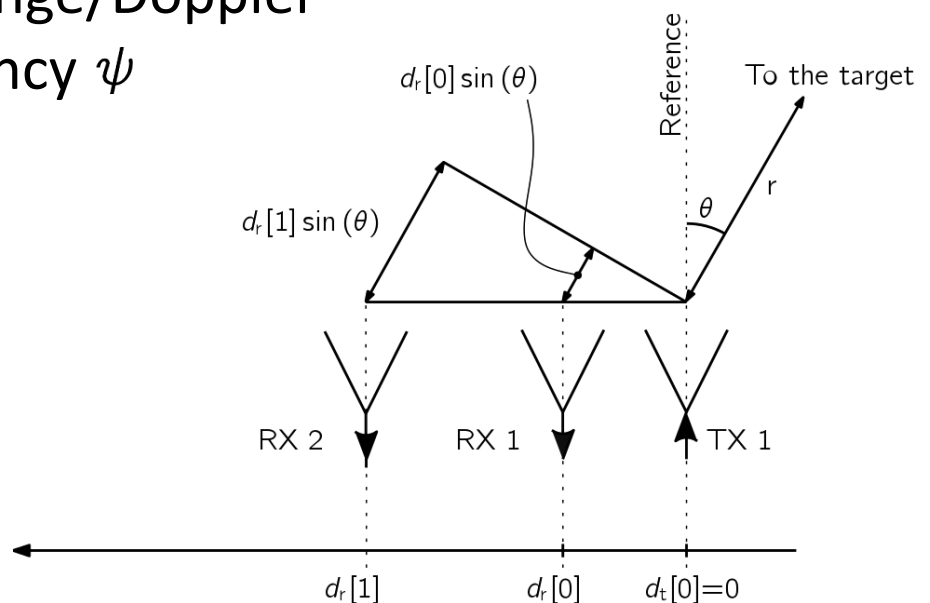
- Multiple antennas are introduced for spatial resolution
- Phased array approach is depicted
- Complex weights are applied by amplitude control and phase shifting
- Circuit requirement: High phase stability between TRX channels



SiGe for mm-Wave and THz

The FMCW Principle

- Single chirp: Range/Doppler coupled frequency ψ

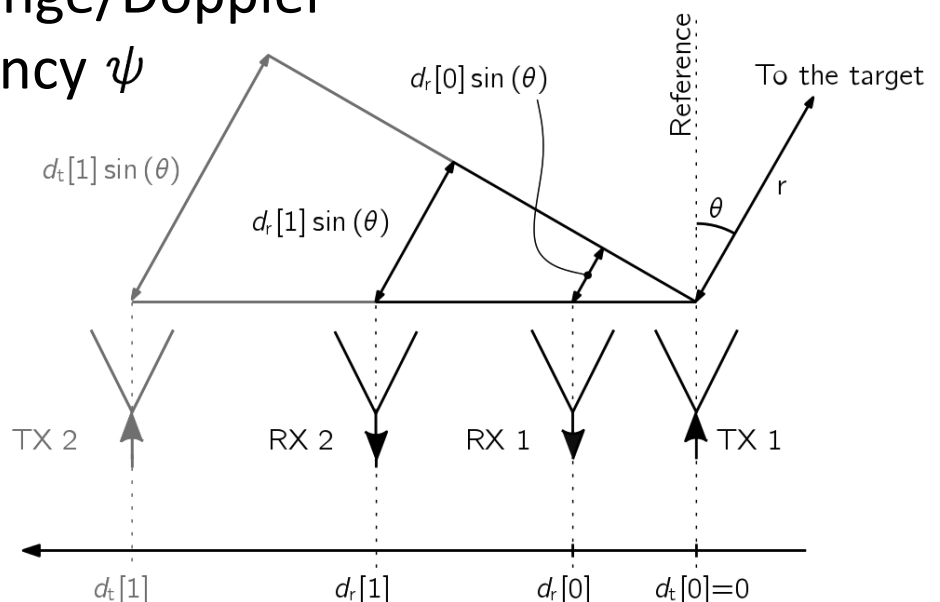


$$s_{IF}[n, m_r] \Big|_{TX1} \approx A \exp \left\{ j2\pi \left(f_0 \frac{2r + d_r[m_r] \sin(\alpha)}{c} + \psi n \right) + \phi_0 \right\}$$

SiGe for mm-Wave and THz

The FMCW Principle

- Single chirp: Range/Doppler coupled frequency ψ



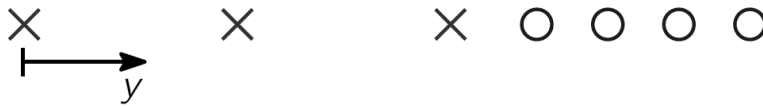
$$s_{IF}[n, m_r] \Big|_{TX2} \approx A \exp \left\{ j2\pi \left(f_0 \frac{2r + (d_r[m_r] + d_t[1])u}{c} + \psi n \right) + \phi_0 \right\}$$

SiGe for mm-Wave and THz

Ref. (2)

Uniform Linear Virtual Array

MIMO array



Associated virtual array



X TX O RX
 ⊙ Overlapping virtual receivers

$$M_{TX} = 3$$

$$M_{RX} = 4$$

$$M_{Vu} = M_{Vu,max} = 10$$

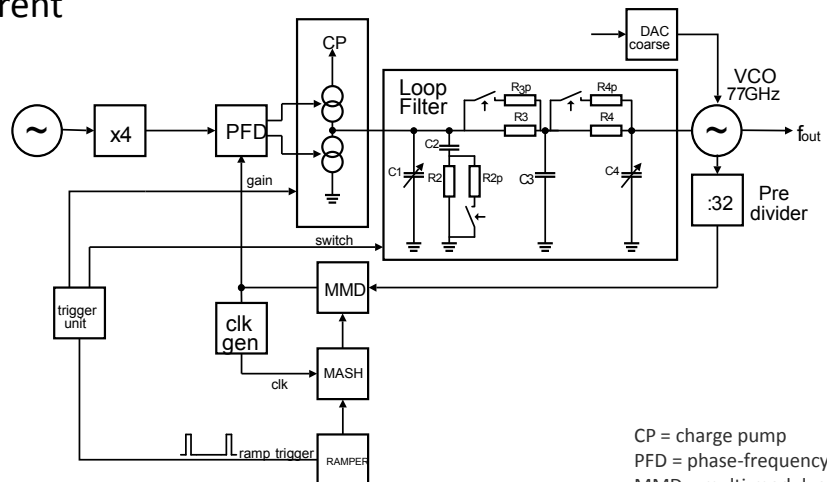
$$M_{Vu} = M_{Vu,max} = M_{TX} \times M_{RX} - M_{TX} + 1$$

Ref. (3)

SiGe for mm-Wave and THz

Agile PLL frequency ramping

- Minimize settling times by switching loop filter bandwidth and charge pump current

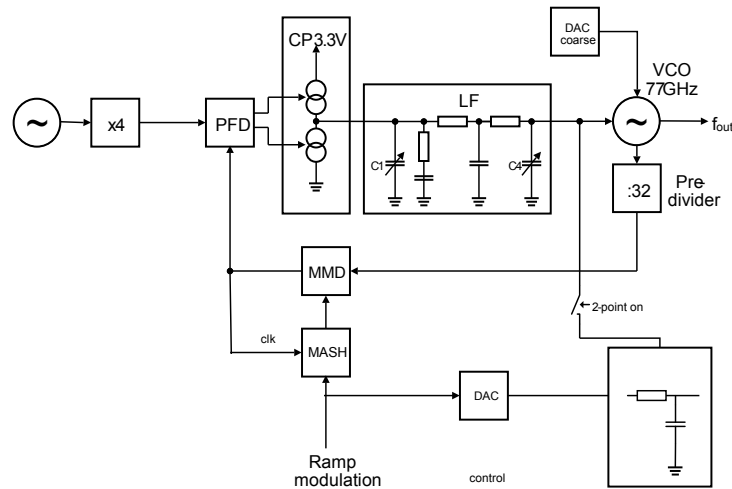


CP = charge pump
 PFD = phase-frequency detector
 MMD = multi-modulus divider
 MASH = noise shaping modulator

SiGe for mm-Wave and THz

Agile PLL frequency ramping

- Boost PLL speed by using two-point modulation



CP = charge pump
PFD = phase-frequency detector
LF = loop filter
MMD = multi-modulus divider
MASH = noise shaping modulator

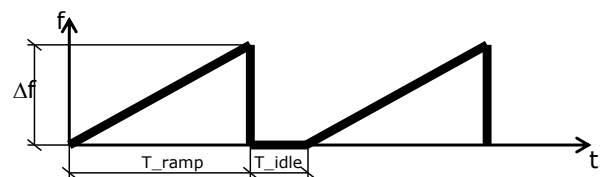
Challenge:

- VCO tuning characteristic is highly variable over the tuning range
- Automatic optimum adjustment of all parameters (charge pump current, loop filter bandwidth, modulator DAC amplitude, coarse tune preset ...)

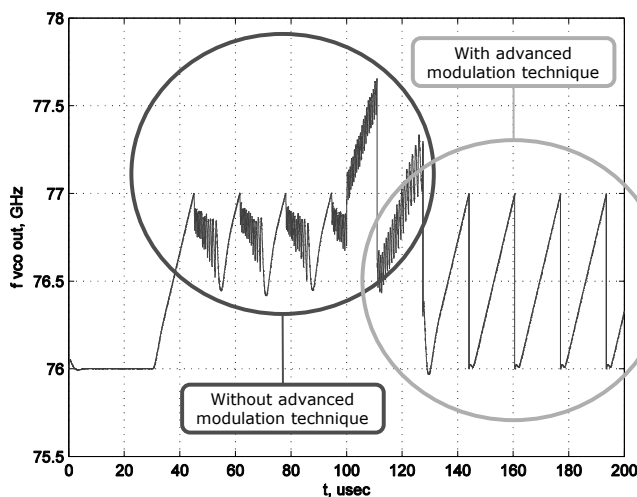
SiGe for mm-Wave and THz

Agile PLL frequency ramping

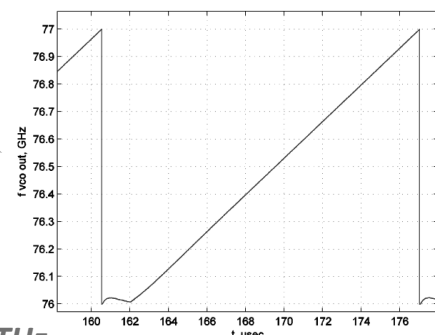
- Advanced PLL concept evaluation for sawtooth ramp scenario: $\Delta f = 1$ GHz; $T_{\text{ramp}} = 15$ μs ; $T_{\text{idle}} = 1.5$ μs



- Results of dynamic evaluation:



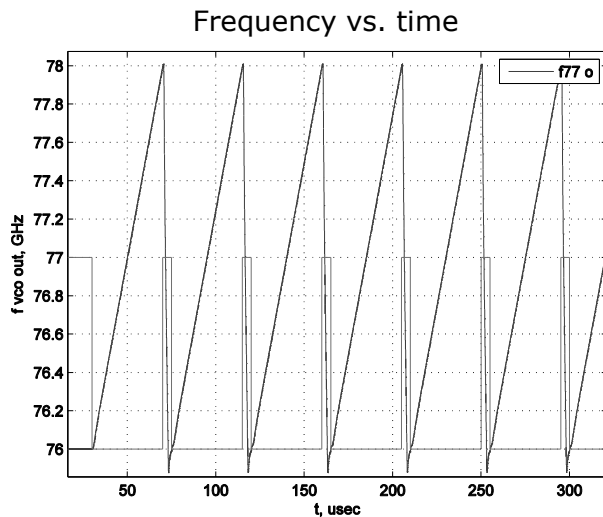
- Very fast ramp scenarios possible
- Linear ramp generation
- No cycle slips for frequency jumps
- Reduced frequency overshoots
- Dead time between ramps significantly reduced
- PN spectrum unaffected



SiGe for mm-Wave and THz

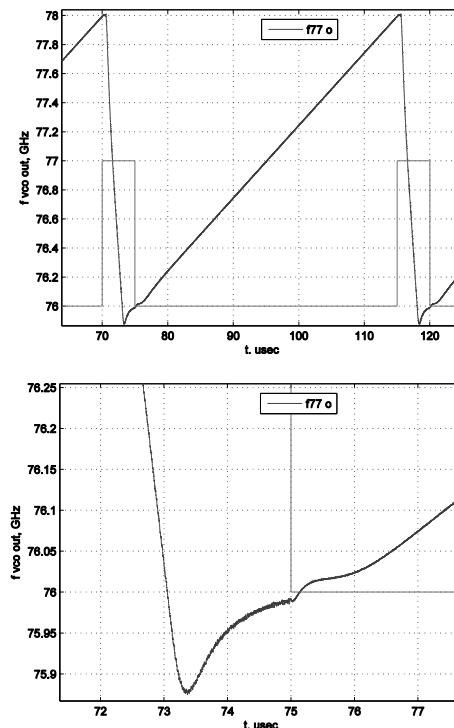
Test Ramp Scenario

- Simulated Ramp scenario with accurate VCO model



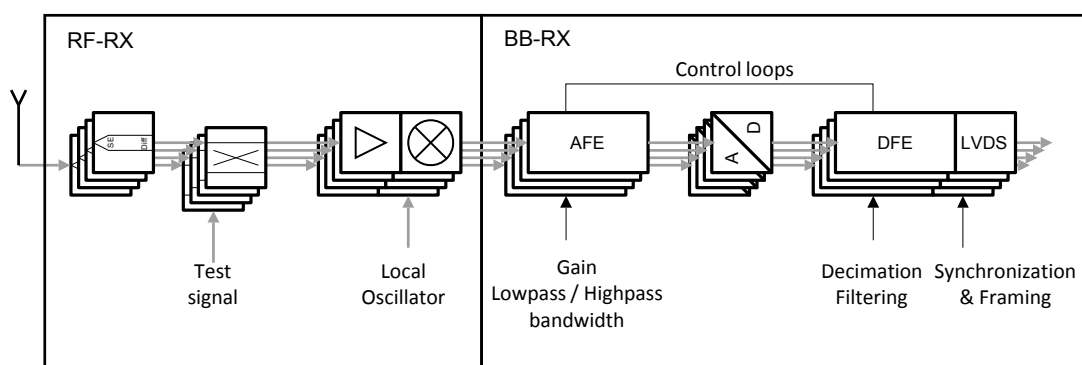
blue: instantaneous frequency
red: boost on / off

Frequency vs. time, ZOOM



SiGe for mm-Wave and THz

Highly flexible RX chain



- Flexibility is achieved by:
 - A high level of configurability in every single block
 - An overall 'supervising' control function to improve applicability
 - Moving as much functionality as possible into the digital domain

AFE = analog frontend
DFE = digital frontend
LVDS = low voltage digital signalling

This challenge is similar to mobile phone receivers supporting multiple standards

SiGe for mm-Wave and THz

Let us take a look outside AR ...

- What other applications could be feasible with similar top level requirements?
- How about a very compact, fully integrated short range sensor?

SiGe for mm-Wave and THz

What could that sensor look like?

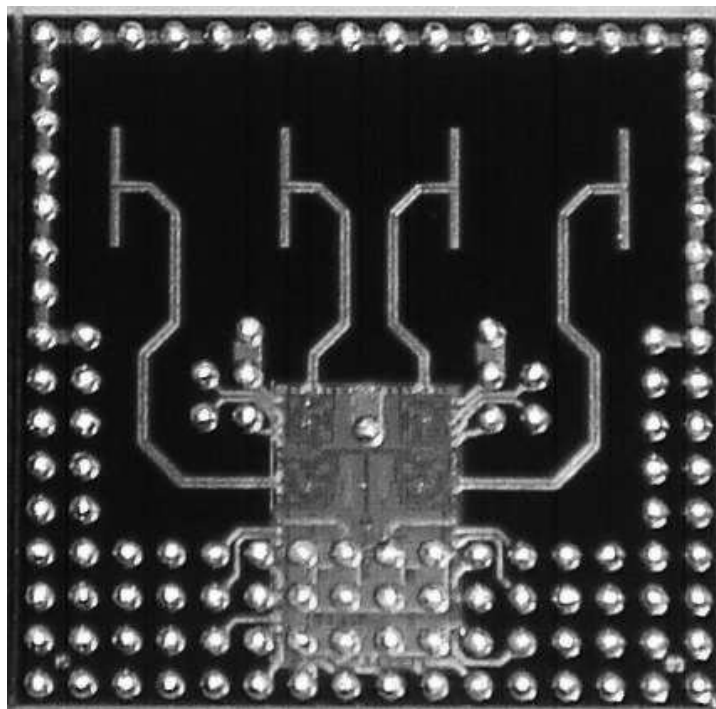
- Integrate the complete radar in a single chip
 - Requires advanced semiconductor technology – B11HFC
- Employ MIMO technique to create a larger array of virtual antennas
- Integrate antennas in the package (AiP)
 - No RF PCB required; simple application
- Use TRX channels instead of separate transmit / receive channels
 - This will yield an even larger virtual array.
- Choose frequency band (Ref. 4) → antenna size, available bandwidth
 - Automotive: 76-77 GHz, 77-81 GHz
 - ISM: 61-61.5 GHz
 - SRD (short range device): 57-64 GHz, 122-123 GHz

SiGe for mm-Wave and THz

Multiple TRX antennas

- Use transmit + receive (TRX) channels instead of individual transmit and receive channels
- Operating frequency: 77 GHz
- Package size: 8 x 8 mm²
- NOTE: This antenna placement has not been optimized for MIMO operation.

(Ref. 5)



SiGe for mm-Wave and THz

Antenna in package (AiP) at 160 GHz

- Circuit design for higher frequencies is feasible with the next SiGe technology step
- Antennas can be integrated in a standard embedded wafer level ball grid array (eWLB) package
- directional antenna
- This design was done in B7HF500, a precursor to B11HFC

(Ref. 6)

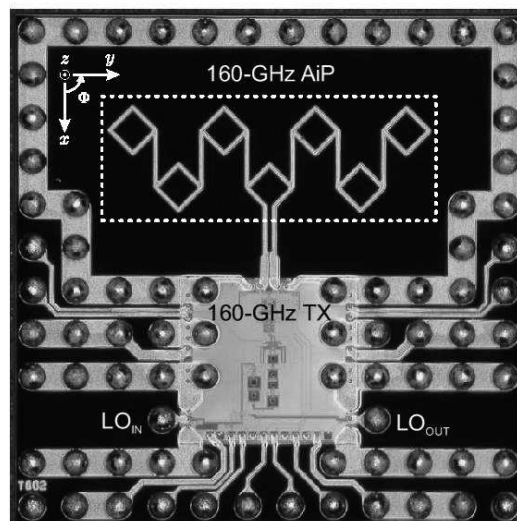
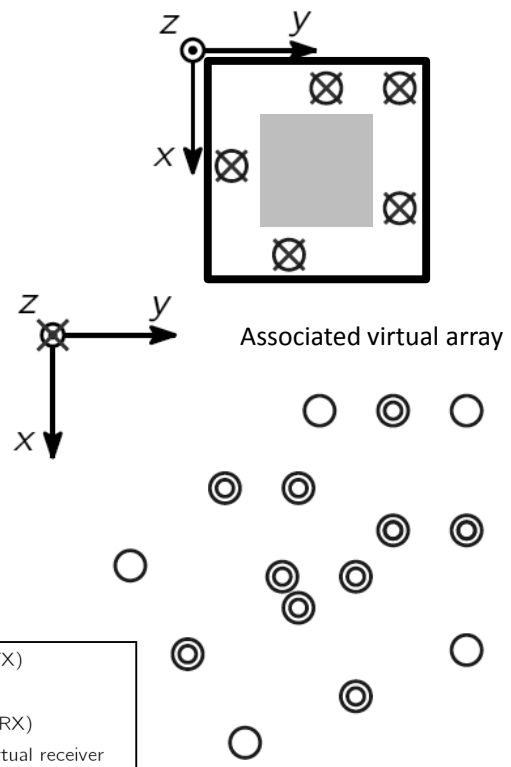


Fig. 6. A microphotograph of the fabricated 160-GHz AiP integrated with the 160-GHz TX chip in a 6 × 6 mm² eWLB package.

Combining AiP and mono-static concept

- Antennas aligned at the periphery of the eWLB package
 - + Maximize achievable aperture
 - + Non-uniform arrangement is possible with MIMO radar (Ref. 2)
- Use TRX channels instead of dedicated TX and RX channels
 - + Best utilization of the available space
 - + Max. $n(n+1)/2$ virtual antennas (Ref. 3)
 - + Redundant virtual antennas
 - Potential blocking of receiver when antenna matching is insufficient
 - Degradation of available dynamic due to duplexing function (TX/RX separation)

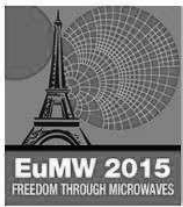


SiGe for mm-Wave and THz

References

- (1) Christoph Wagner: Application-Driven Design and Characterization of a 77-GHz Radar Transceiver, EuMW 2013, Workshop W 20
- (2) R. Feger, C. Wagner, S. Schuster, S. Scheiblhofer, H. Jäger, A. Stelzer: A 77-GHz FMCW MIMO Radar Based on an SiGe Single-Chip Transceiver, IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 57, NO. 5, MAY 2009
- (3) Christian M. Schmid, Reinhard Feger, Clemens Pfeffer, Andreas Stelzer: Motion Compensation and Efficient Array Design for TDMA FMCW MIMO Radar Systems, EUCAP 2012
- (4) ECC/CEPT: ERC Report 25: The European Table of Frequency Allocations, May 2015; <http://www.ero-docdb.dk/Docs/doc98/official/pdf/ercprep025.pdf>
- (5) A. Hamidipour, A. Fischer, M. Jahn, A. Stelzer: 160-GHz SiGe-Based Transmitter and Receiver with Highly Directional Antennas in Package, EUMW 2013
- (6) Wojnowski et al: A 77-GHz SiGe Single-Chip Four-Channel Transceiver Module with Integrated Antennas in Embedded Wafer-Level BGA Package, ECTC 2012

SiGe for mm-Wave and THz



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(Part II)

WS12: EuMIC - SiGe for mm-Wave and THz



Content – Part II

- Why monostatic radars?
- Current implementation vs. quasi-circulator (QC)
- Antenna mismatch and leakage cancelation
- Impedance tuner – bipolar vs. BiCMOS

SiGe for mm-Wave and THz

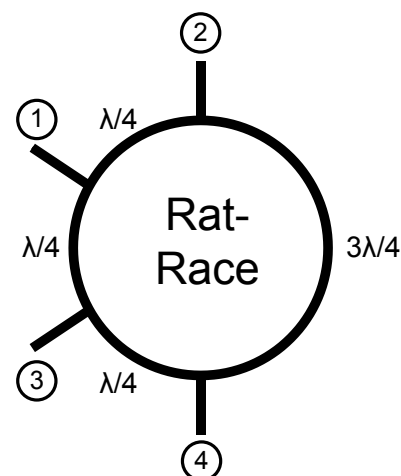
Monostatic radar

- Why investigation in monostatic radars?
 - Monostatic radars reduce the physical area consumption for antennas and the RF transitions from chip to board by a factor of 2.
 - High resolution radars require many channels and the amount of RF ports in a package are limited.
 - In respect of a antenna in package system, only a few antennas can be placed.

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Current implementation

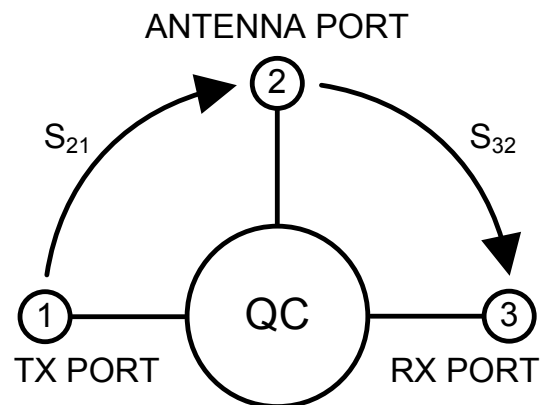
- The TX/RX separation in 77 GHz automotive radar systems is usually done by passive structures like a 180° ring hybrid so called rat-race coupler.
- The rat-race exhibits a theoretical insertion loss of 3 dB in each direction, which directly degrades the noise figure. In practice, around 4.5 dB are measured.
- The relatively large physical dimension of the rat-race is also a problem in multi channel systems.
- Therefore the investigation of active TX/RX separation units like a Quasi circulator(QC).



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Active Quasi Circulator

- A QC performs TX/RX separation of transceiver modules.
- The QC consists of a TX, an ANTENNA and an RX port.
- Circulators offers power flow only in one direction.
- QCs additionally provide isolation from RX to TX port.

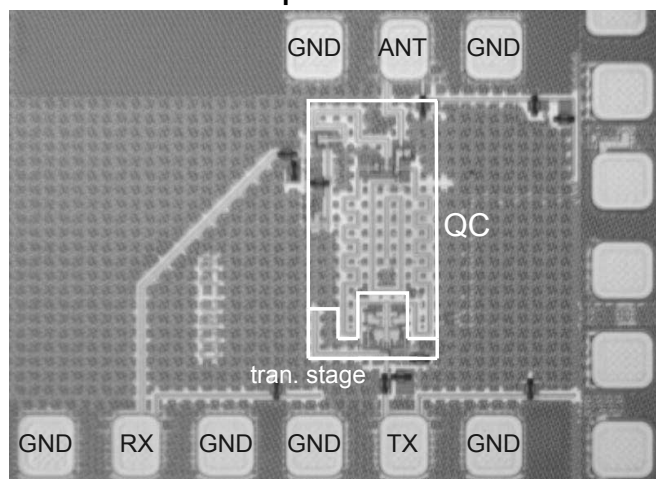


Ref. (1)

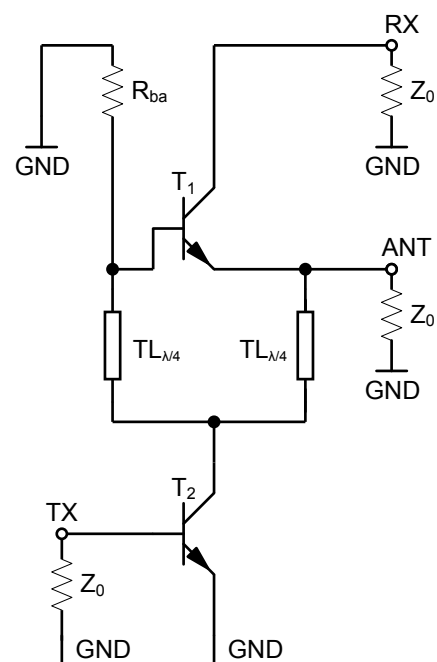
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Active QC structure

- In general, the QC consists of two BJT transistors, two $\lambda/4$ -transmission lines and one resistor.
- The power flow can be split in a TX- and an RX- path.



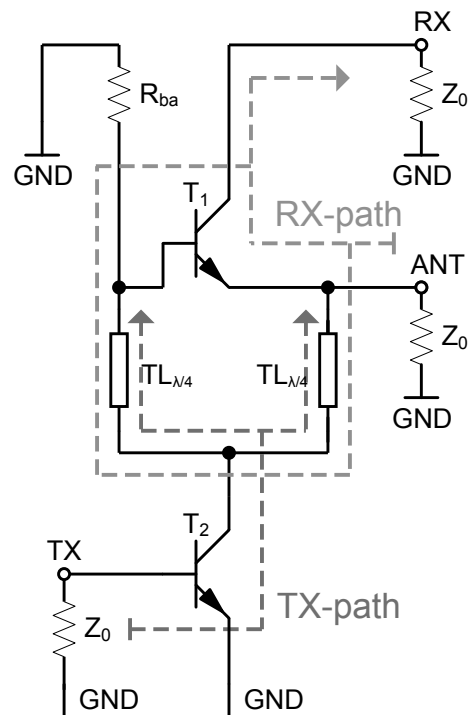
Ref. (2)



SiGe for mm-Wave and THz

Power flow in the QC

- If $R_{ba} = Z_0$, the transmit signal appears in-phase at the base and the emitter of T_1 and therefore the signal is isolated from the RX port.
- T_2 is assumed as unilateral.
- The receive signal appears out-of-phase at the base and the emitter of T_1 . Consequently, it is amplified by T_1 and transferred to the RX port.



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QC vs rat-race

- In theory, 3 dB of the TX signal is terminated by a resistor in both approaches.
- Assuming T_2 in the QC as unilateral, none of the receive signal is dissipated. This involves an improvement over the rat-race implementation.
- As the QC is an active device, T_1 adds some noise to the receive signal.
- Therefore, when comparing a QC and a rat-race system with respect to noise figure, the whole receiver including the mixer has to be taken into account.
- Based on the Friis formula, the shown QC system offers a better total NF if the following stages have a NF worse than 9.1 dB (2). For comparison, a published 77 GHz mixer processed in the same technology is stated with around 14.9 dB NF (3).

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Mismatch at antenna port

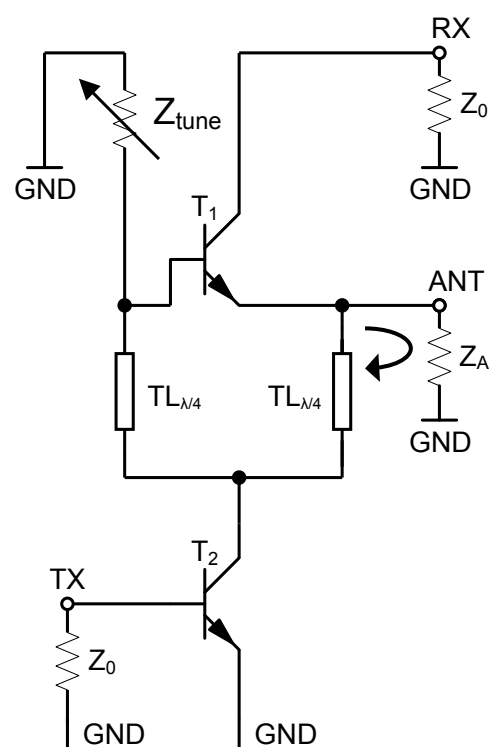
- One of the main problems in monostatic radars is the mismatch at the antenna port due to process variation.
- It degrades the isolation performance in the QC as well as in a rat-race implementation.
- This can be solved by a so called leakage canceler in the RF part or by a DC-offset compensation after the down conversion mixer in the IF domain.
- In case of a DC-offset compensation, the mixer is still blocked by the reflected transmit signal and generates harmonics in the IF spectrum.
- Therefore a leakage canceler solution is preferred to relax the requirements on the mixer.

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Leakage canceler for the QC

- Proposed solution is a impedance tuner instead of the resistor R_{ba} .
- By setting the impedance of the tuner to the actual antenna impedance

$$Z_{\text{tune}} = Z_A$$
 isolation is achieved again.
- As Z_A is not monitored in a system directly, the tuner has to be controlled based on the DC-offset of the mixer.
- Also other effects like process variation can be compensated in this way.



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Tuner implementation

- In a pure bipolar process, the impedance tuners usually are implemented with varactors, which require an additional digital/analog converter (DAC) for controlling them.
- A BiCMOS process offers the tuner implementation based on FET switches, which can be digitally controlled by conventional SPI interface.
- This makes the system compact and simple to control.

SiGe for mm-Wave and THz

Conclusion

- The monostatic concept is useful for applications in limited space
- The systematic penalty by using a passive coupler, e.g., a rat-race can be avoided with an active QC.
- Test circuits have already been implemented.
- New concepts for leakage cancelling are under investigation.
- A BiCMOS process facilitates the implementation of a compact system

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