Oscillation-based built-in self-testing

A promising approach for RF systems in orbit

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National Space Week, 29-31 August 2023, Pretoria, South Africa

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Agenda

- What is Built-In Self-Testing?
- Why RF?
- Risks to electronics
- Effect on electronics
- RF Built-in self-testing techniques
- Introduction to OBIST
- Progress on RF OBIST
  - Fault detection in RFCMOS
  - RF Performance estimation
  - System testing
  - Phase shifter calibration
  - Application of machine learning
- Conclusion

What is Built-In Self-Testing?

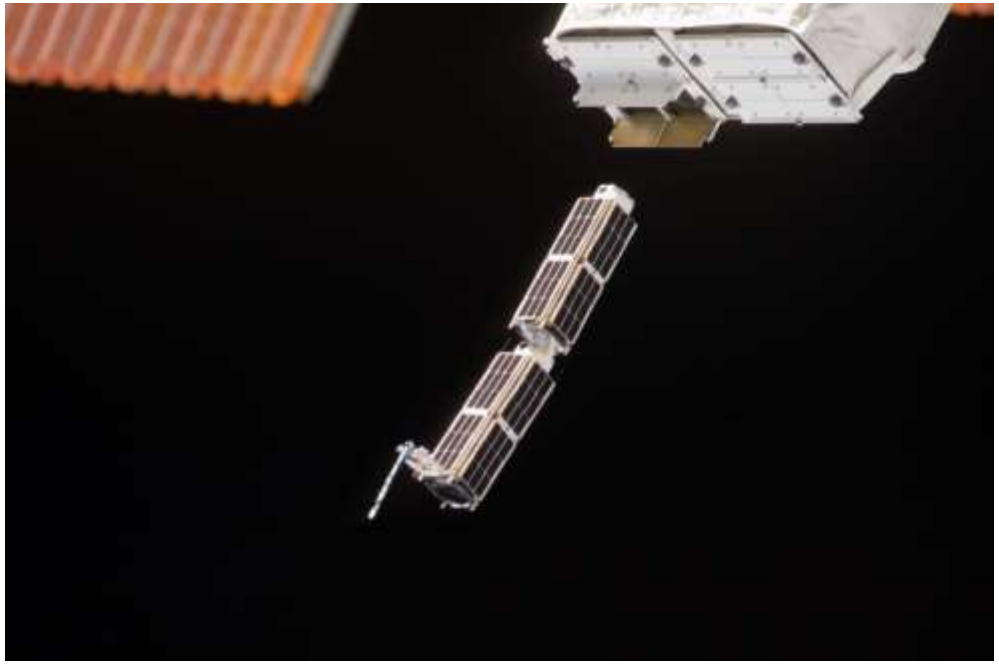
Welcome to the challenge of built-in self-testing

What does BIST tell us?

- Fault-driven testing
  - Is there a fault somewhere? (Fault detection)
  - Where is the fault? (Fault identification)
  - How bad is the fault? (Fault diagnosis)
- Performance-driven testing
  - How well does it work? (Performance estimation)
  - Does it work well enough? (Specification checking)

RF & microwave in space

- Telemetry, Tracking, Command (TT&C)
- Data downlink / uplink
- Navigation
- Payloads
  - Communications / broadcasting
  - Passive imaging, radiometers
  - Active imaging, radar



Risks to (RF) electronics

- Shock, vibration
- Thermal cycles
- Vacuum outgassing
- Ionizing radiation
  - Transient effects (e.g. SEE)
  - ***Long-term damage (TID, DD)***
  - Need built-in self-testing in orbit
    - Extend mission life
    - Learn from failure

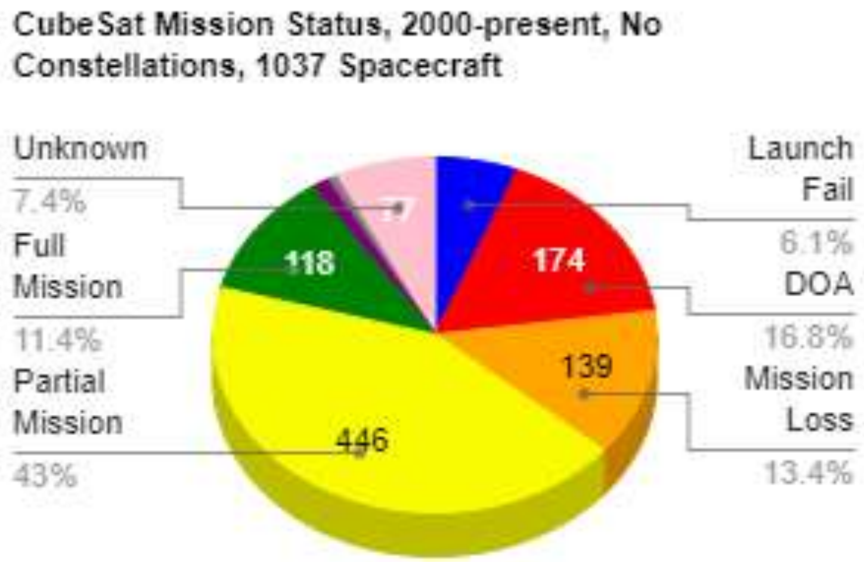
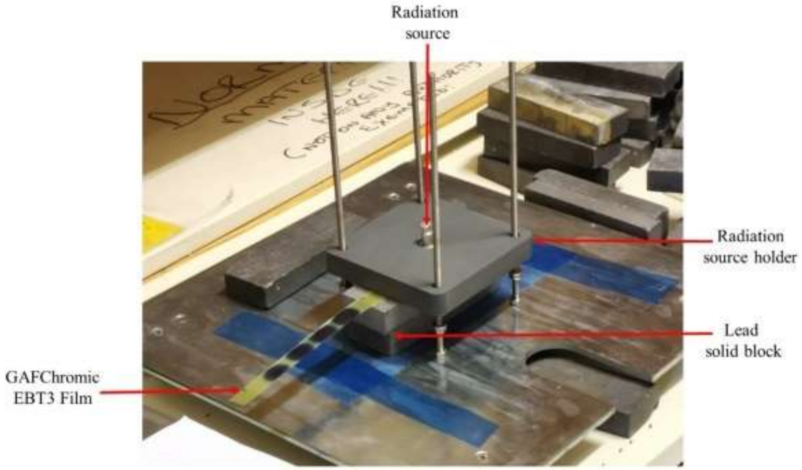


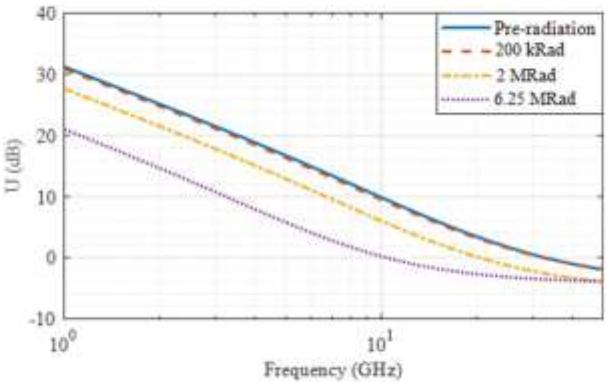
Image credit: Michael Swartwout, Seradata
https://sites.google.com/a/slu.edu/swartwout/cubesat-database

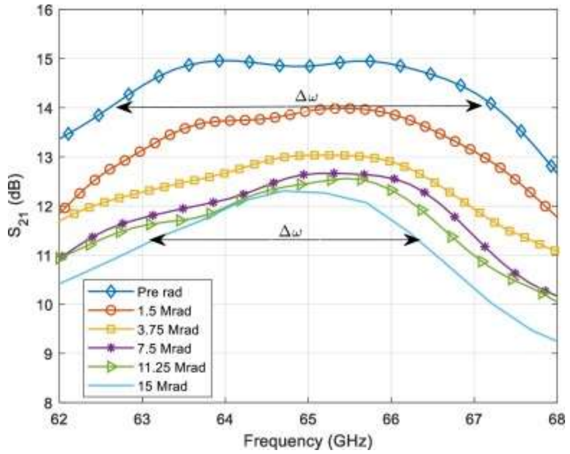
Effect on (RF) electronics

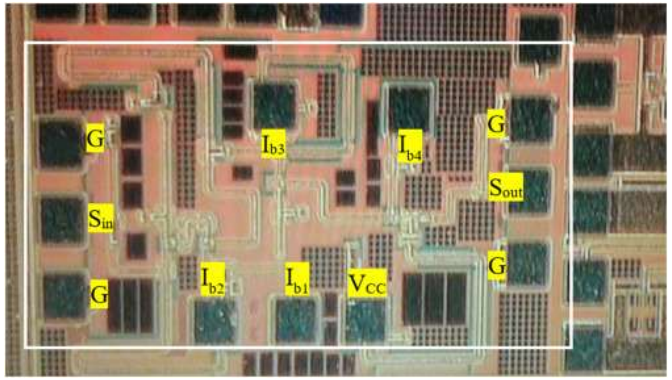
- Device level effects
  - Lower transconductance
  - Increased *R*, *C* parasitics

- Circuit-level effects
  - Decreased gain
  - Increased noise
  - Reduced bandwidth









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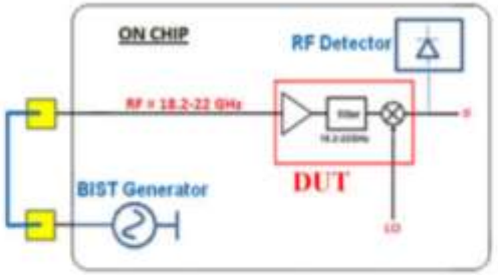
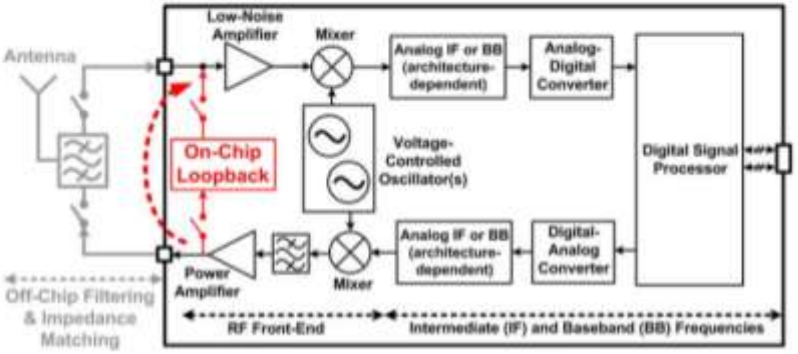
BIST techniques in RF

- Source testing
  - Tone or modulated noise
  - Reliable source, detector
- Loopback
  - Full chain tested
  - Need TX & RX, same band
- Surrogate / dummy device
  - No performance impact on true device
  - Assume health-by-proximity
  - Works at device level





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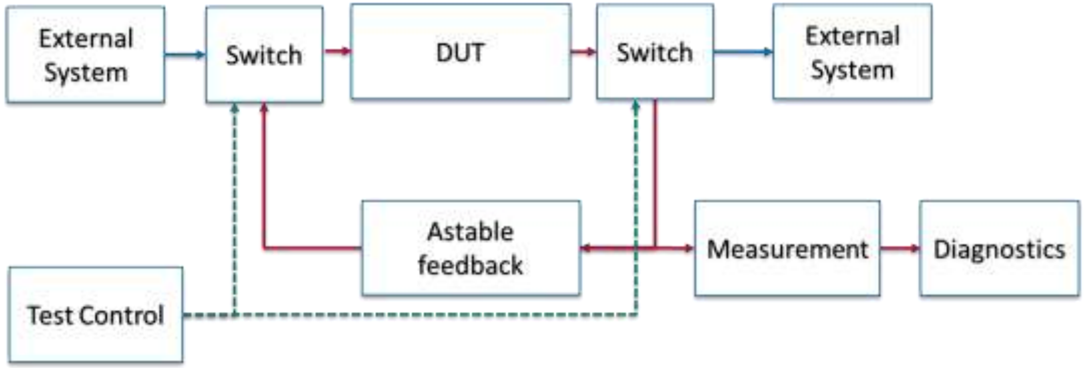
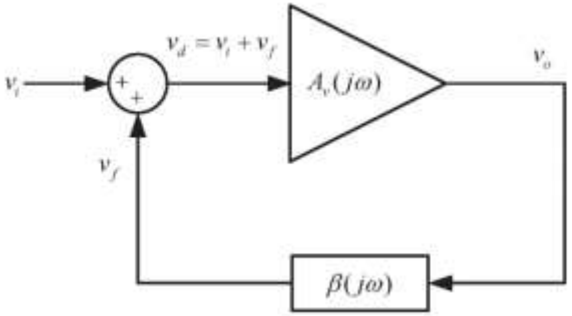
- Onabajo et al, IEEE Tran. Circ. Syst. II, 56(6), 2009.

Introduction to OBT

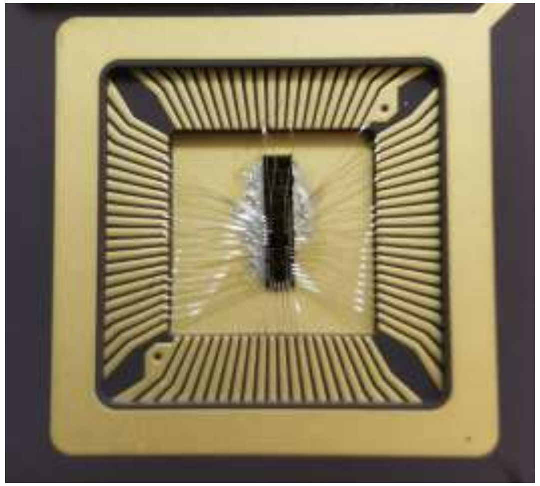


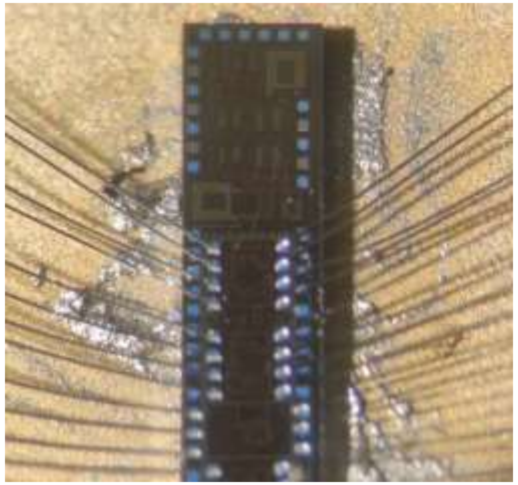
- Barkhausen stability criteria
- Any system can oscillate with
  - Enough gain
  - The right feedback
- Oscillation tells us something about the system
  - Frequency
  - Power in harmonics
  - Time series data



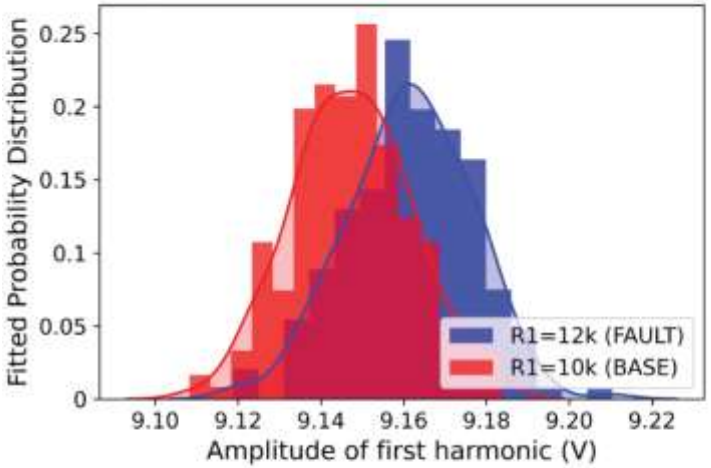
$$\frac{V_o}{V_i} = \frac{A(j\omega)}{1 - A(j\omega)\beta(j\omega)}$$

Advantages of RF OBIST

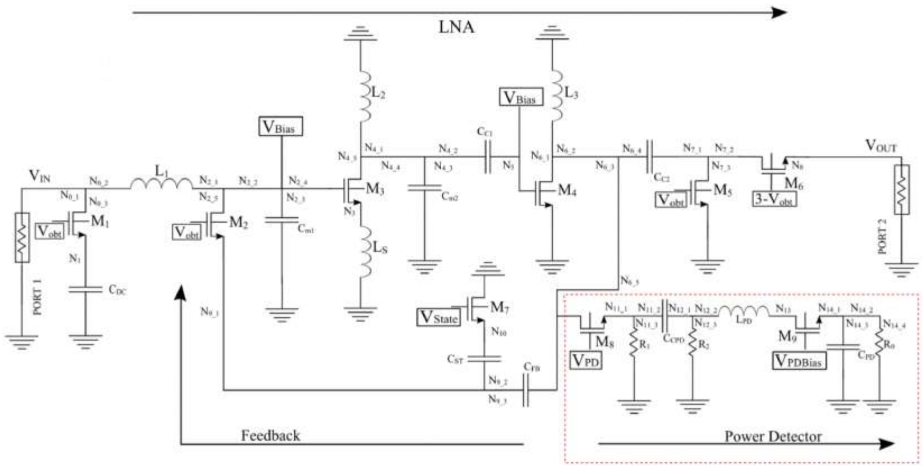




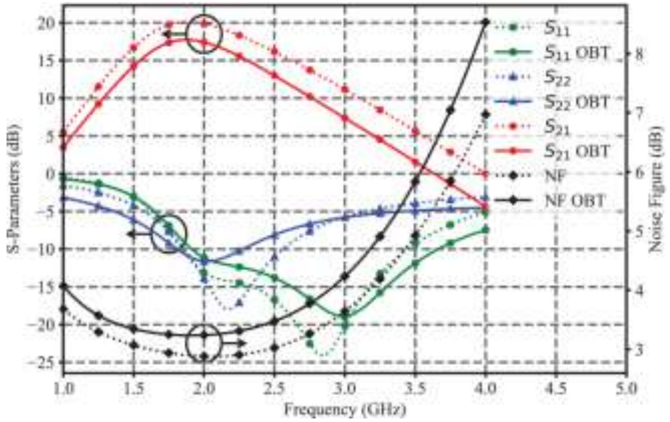
- No RF source required
- Tests true RF performance
  - No surrogates
- Reach inaccessible systems, devices
- Reduce production cost
  - No RF I/O required
- In-situ testing in harsh environments (e.g. space)
- *Cannot digitize RF oscillation*
  - *Can <u>filter</u> and <u>measure power</u>*
- *Variability is a problem!*

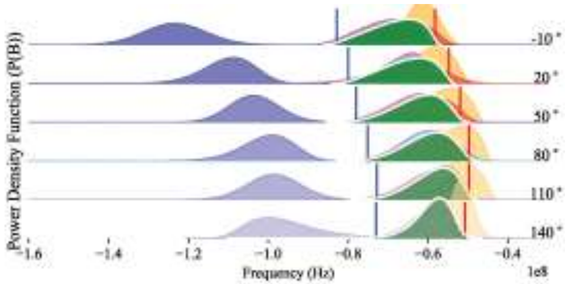


Fault detection in RF CMOS



- 2.4 GHz LNA in 0.35um CMOS
  - Power detection thresholds
  - Filtered for frequency detection
- Monte Carlo simulation
- Injected catastrophic faults
- PVT dependence confirmed
- 1/20 test escapes, 1/52 yield loss
- Dynamic thresholds work best
  - Needs temperature
- Extreme static threshold almost as good
- *We need to do better*
  - *Performance estimation?*





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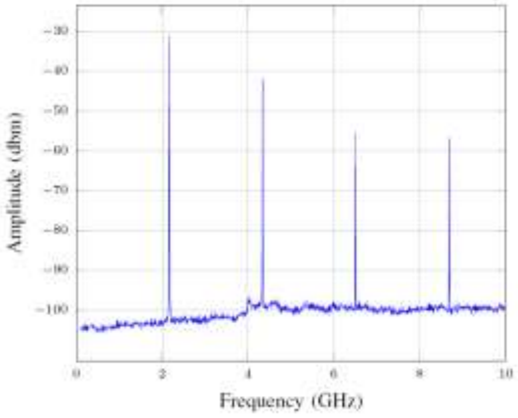
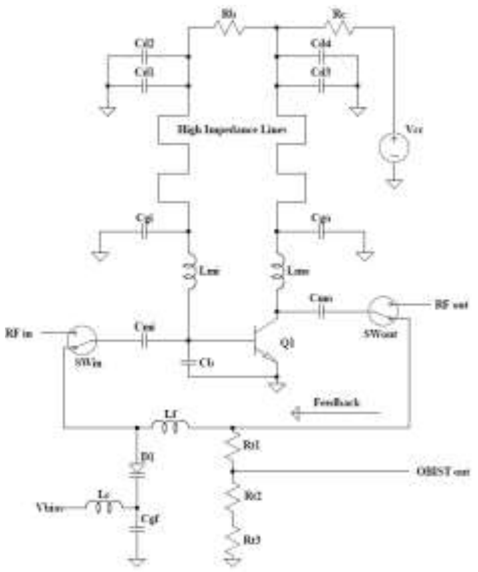
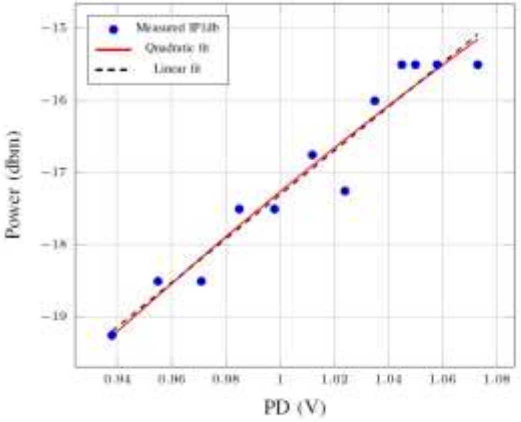
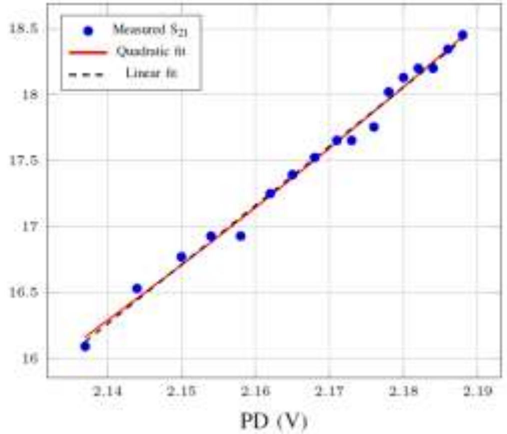
RF performance estimation

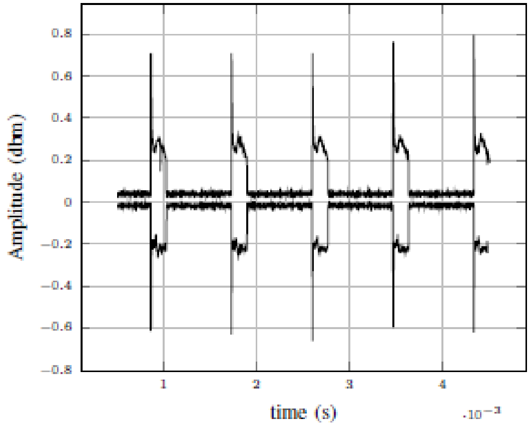
- 2.4 GHz LNA in RFPCB
  - Power detection
  - Harmonics measured
  - Frequency = Filtered power
- Excellent performance estimation
  - Gain, IP1db, IMD3
- ***Self-quenching mode***











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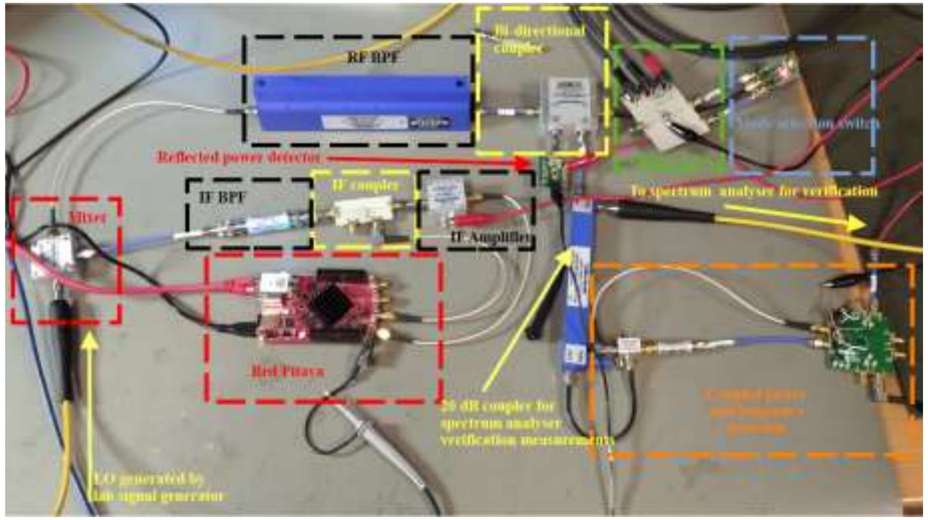
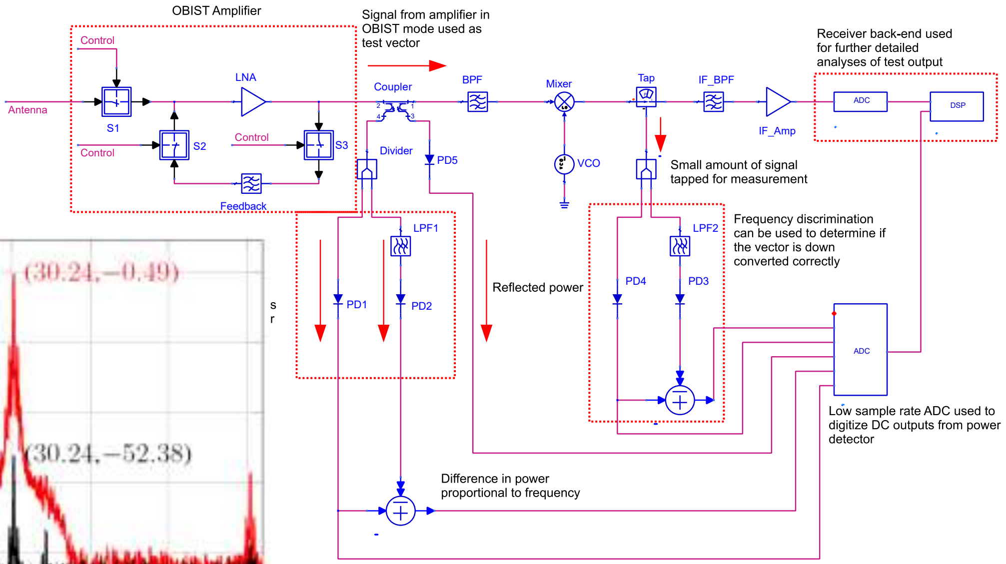
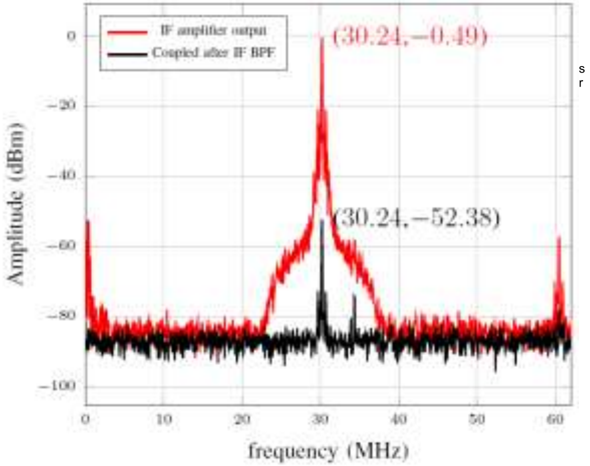
System testing

- 2025 – 2110 MHz receiver
- Use OBIST LNA as system source
  - Power detectors through chain
  - IF also monitored
- Simple fault detection
  - Decrease in LO power
  - High impedances between modules
  - IF Amplifier gain decrease







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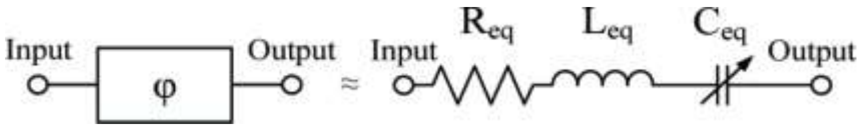
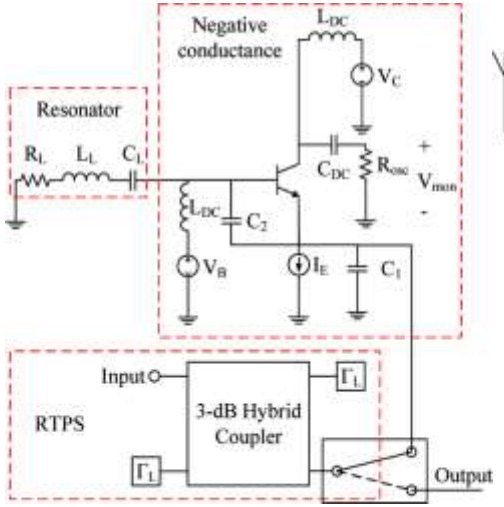
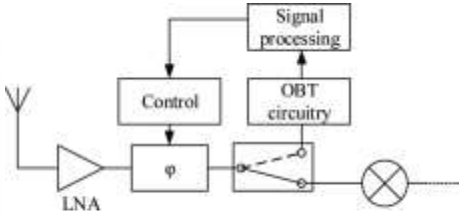
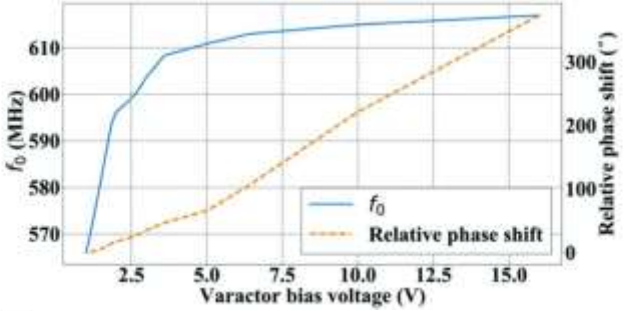
Phase shifter calibration

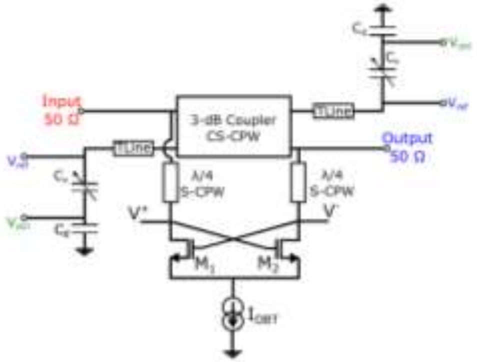


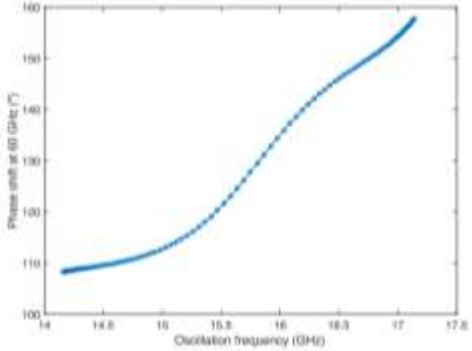
- Phase shifter = variable capacitor
  - RLC tank far below resonance
  - Far below f_0!
  - Switch phase shifter to R_{neg} circuit
  - $f_{osc} \propto \varphi$
  - Low-pass filter: $f_{osc} \propto P_{out}$
- Use phase shifter in feedback loop
  - Approximate as tuneable LC tank
  - Quarter-wave line isolation

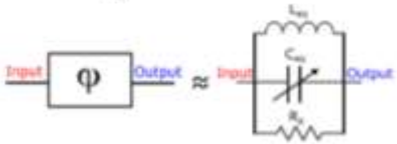












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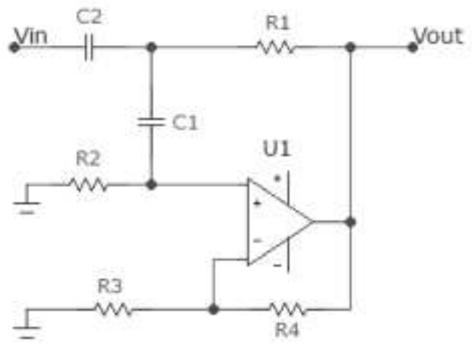
- Margalef-Rovira et al, An Oscillation-Based Test Technique for On-Chip Testing of mm-Wave Phase Shifters, Proc. VTS, 2018.

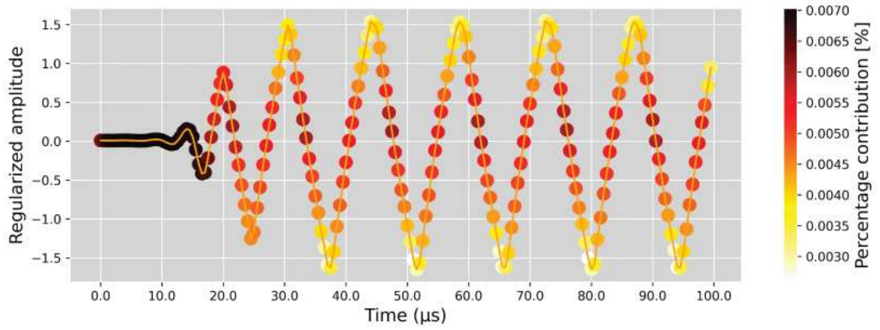
First demonstration of Machine Learning

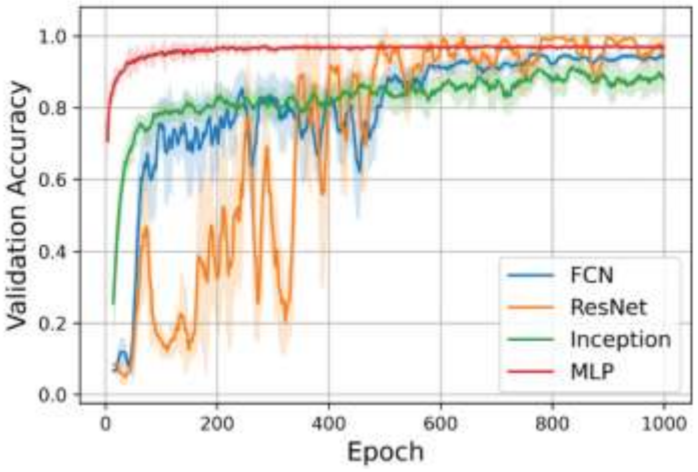
- Baseband OpAmp HPF
- Injected parametric faults
  - Fault classification
- Deep learning > Statistical
  - Both better than harmonic analysis
- ***Start-up region NB!***

Defect label	Component	Nominal value	Fault value
BASE	-	-	-
D1A	R1	10kΩ	10kΩ + (α × 10kΩ)
D1B	R1	10kΩ	10kΩ - (α × 10kΩ)
D2A	R2	10kΩ	10kΩ + (α × 10kΩ)
D2B	R2	10kΩ	10kΩ - (α × 10kΩ)
D3A	R3	10kΩ	10kΩ + (α × 10kΩ)
D3B	R3	10kΩ	10kΩ - (α × 10kΩ)
D4A	R4	750Ω	750Ω + (α × 750Ω)
D4B	R4	750Ω	750Ω - (α × 750Ω)
D5A	C1	22nF	22nF + (α × 22nF)
D5B	C1	22nF	22nF - (α × 22nF)
D6A	C2	22nF	22nF + (α × 22nF)
D6B	C2	22nF	22nF - (α × 22nF)

*The α indicates the fault size (0.2, 0.5, or 0.9)







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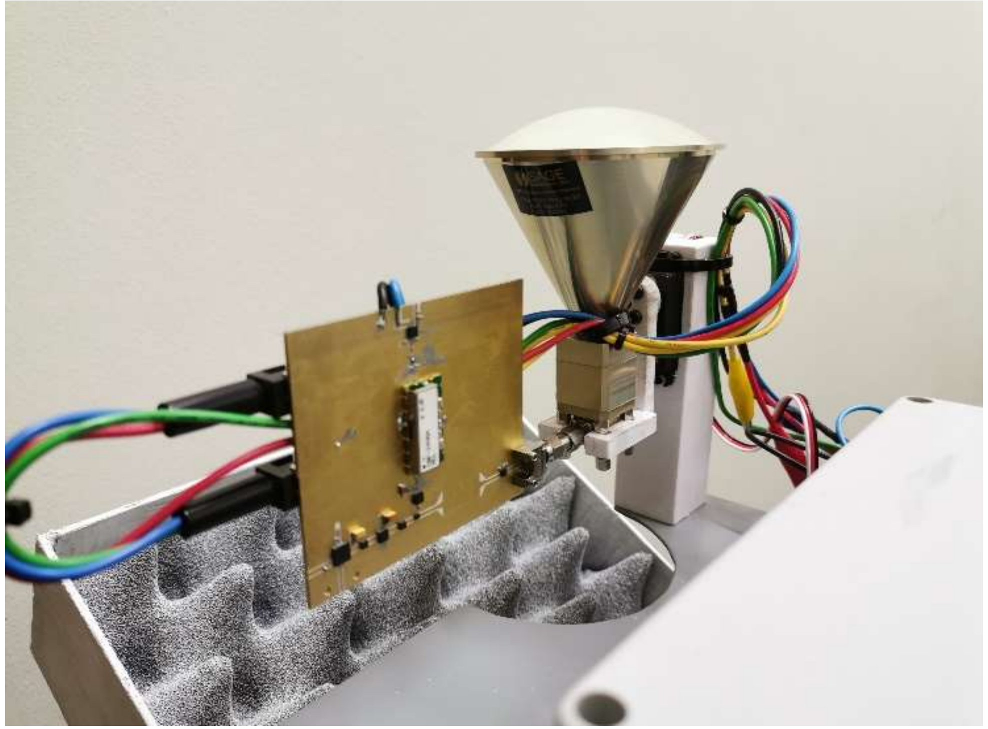
Conclusion

- RF OBIST is promising test technique
  - No test source required
  - True RF performance measured
- Can be used at device and system level
- Variety of data
  - Pass / go fault detection
  - Fault identification
  - Performance estimation
  - Calibration data
- Next steps
  - Full transceiver test
  - Wideband testing with bandwidth estimation



THANK YOU

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