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SAN DIEGO 2023

TH1B-4

Non-Invasive Internal Body Thermometry with On-Chip GaAs Dicke Radiometer

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PFI-TT

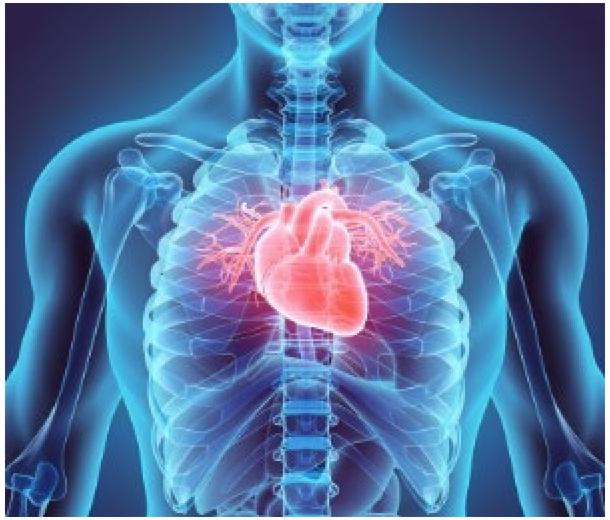
Outline

- Background & Motivation
- Radiometer Overview
- Near-Field Antenna Design
- MMIC Switch and LNA Design
- Measurements and Temperature Estimation

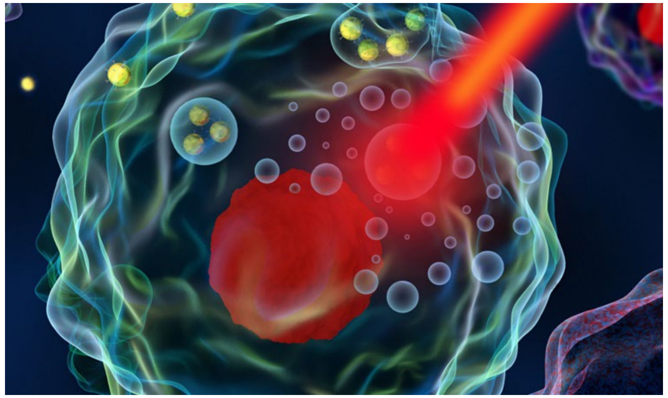
Background & Motivation

- Various medical applications to benefit from internal tissue temperature

Cardiac surgery[1]



Hyperthermia treatment[2]



Sleep disorder[3]

... and many others

Current Methods

- Invasive methods
  - Needle probes and radio pills
- MRI
  - High-cost and non-wearable
- Heat-flux device
  - Sub-cm measurement depth

[4]

[5]

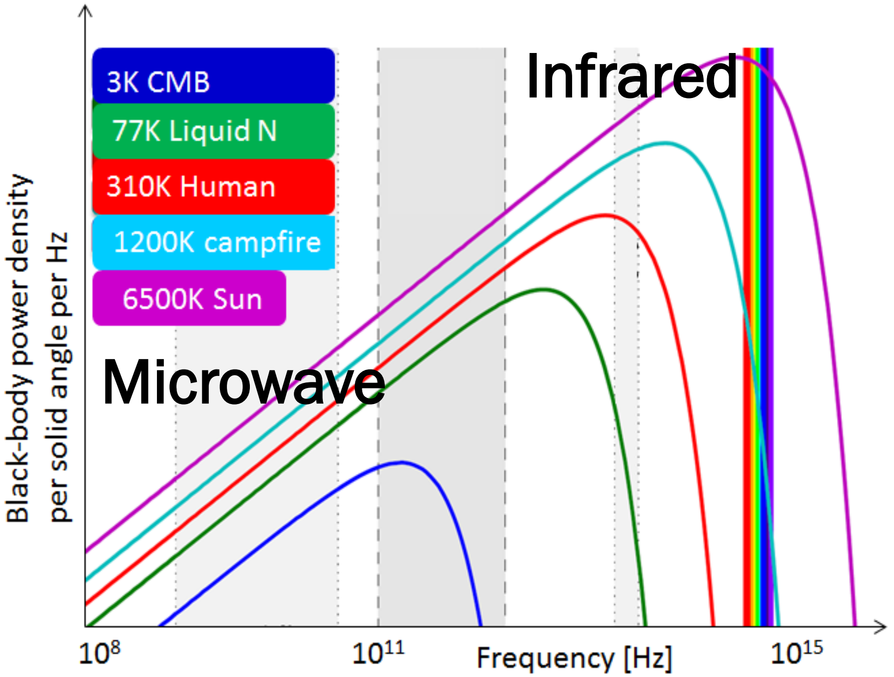
❖ Microwave radiometer is a non-invasive and compact device that measures thermal noise power emitted from a stack of tissues.

Black Body Radiation

- Black body radiation: all materials at non-zero temperature emit electromagnetic energy across the entire spectrum
- The power spectral density (W/Hz) is:

$$p = \frac{hf}{e^{hf/kT} - 1}$$

- For a human, the black-body curve (red) peaks in the infrared (penetration into tissues: ~1mm)

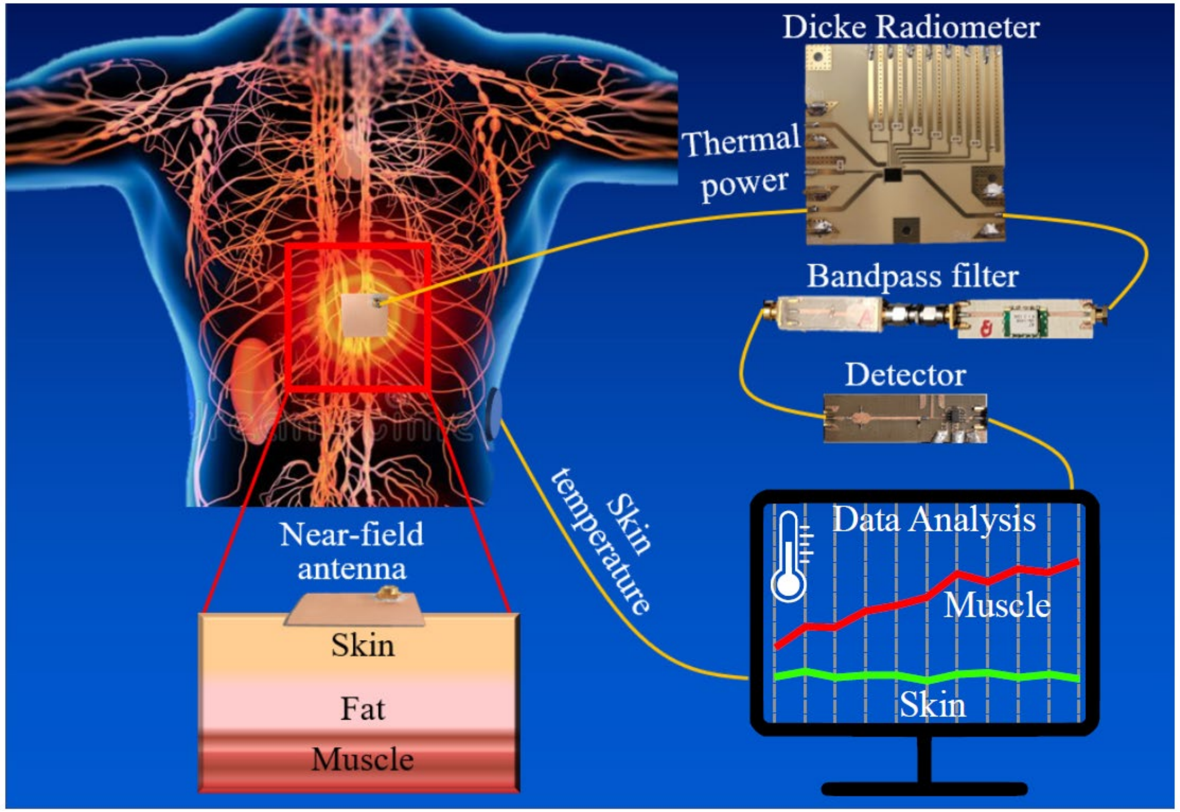


Passive Microwave Thermometry

- At lower microwave frequencies, sensing depth is a few cm

$$p = \frac{hf}{e^{hf/kT} - 1} \approx kT$$

- Near-field antenna attached on skin to receive thermal noise

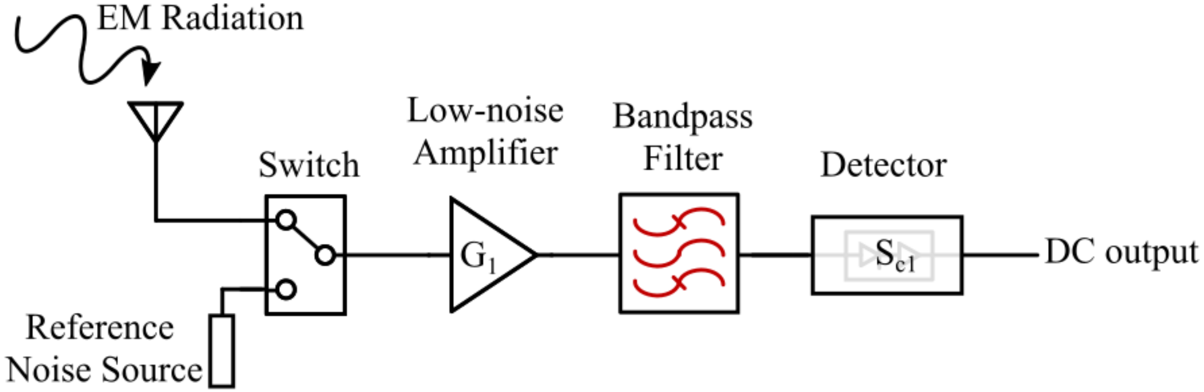


❖ "Quiet" radio astronomy band: 1.4-1.427GHz (2% BW)

❖ Compromise between sensing depth, low RF interference and size

Radiometer Overview

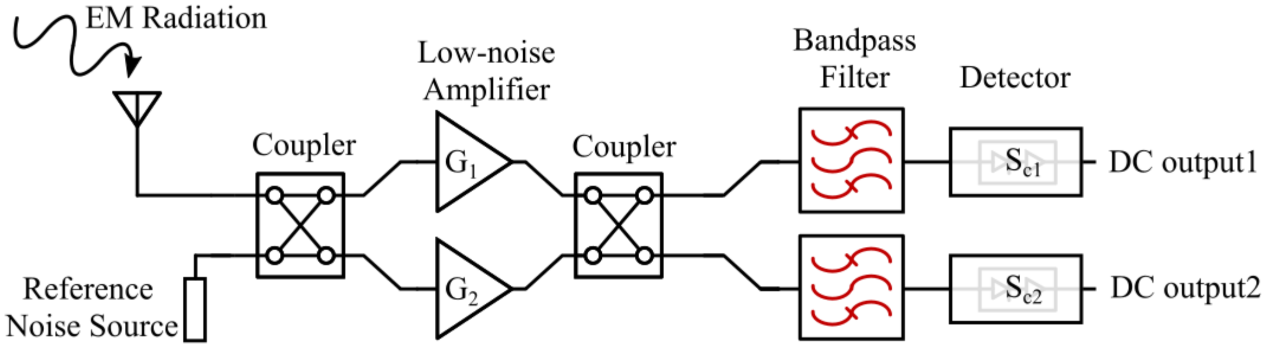
Dicke Radiometer



- Less number of components ☺
- Allows calibration for gain fluctuation ☺
- Time on-target limited ☹
- Switch is lossy ☹

$$\Delta T = \frac{2\,T_{sys}}{\sqrt{\Delta f\ \tau}}$$

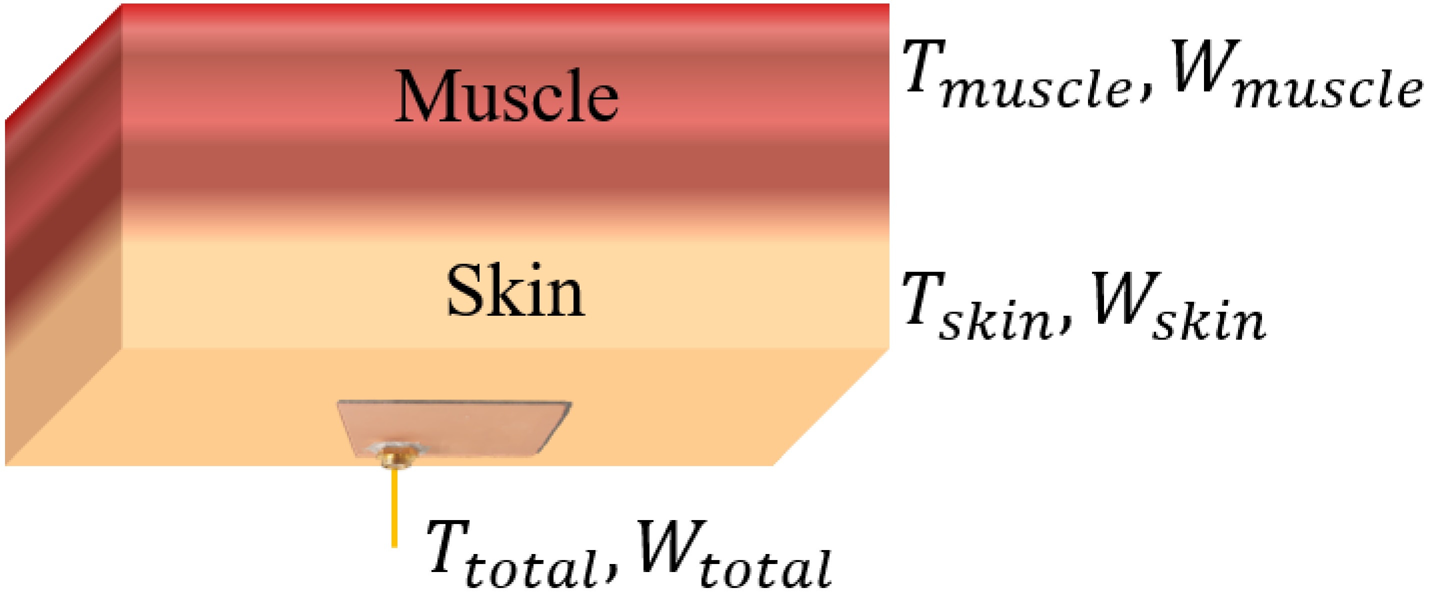
Correlation Radiometer



- Continuous measurement of both input ☺
- Lower sensitivity to impedance mismatch ☺
- Sensitive to gain fluctuation of detector ☹

$$\Delta T = \frac{\sqrt{2}\,T_{sys}}{\sqrt{\Delta f\ \tau}}$$

Temperature Measurement



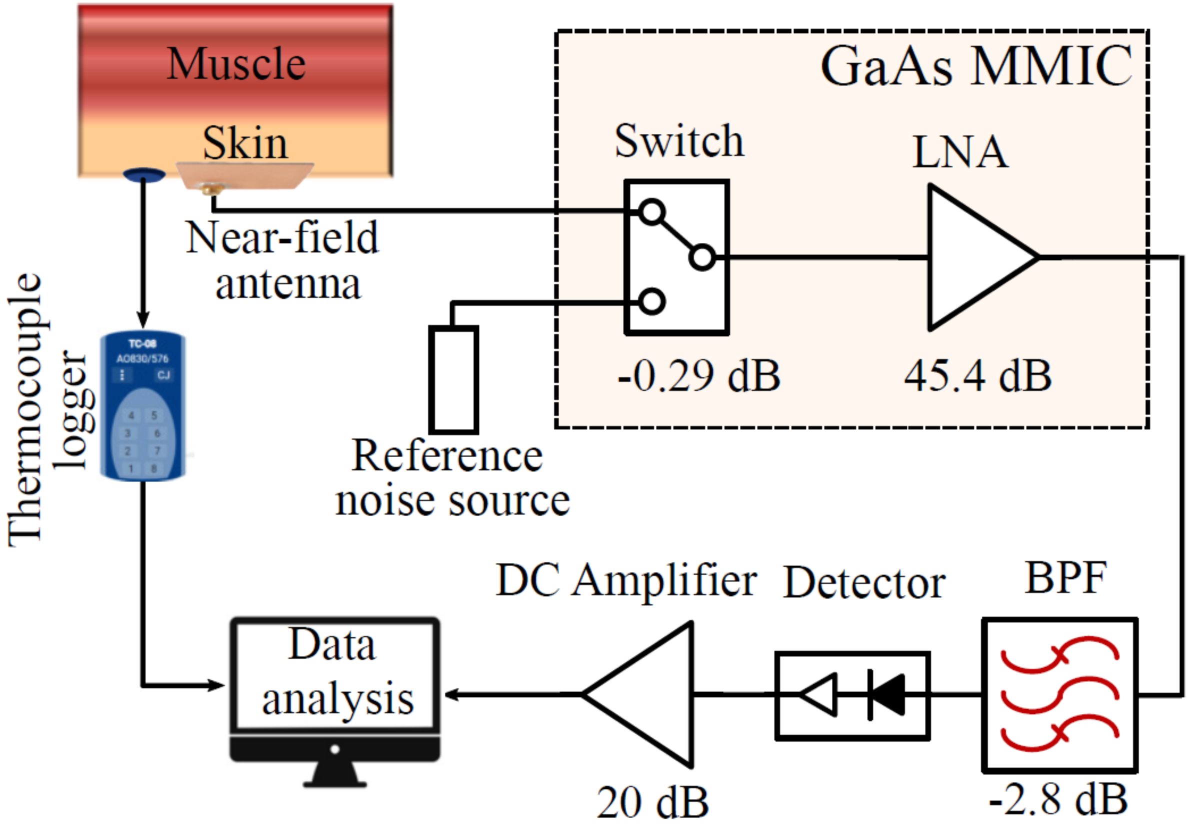
$$T_{total} = W_{skin}T_{skin} + W_{muscle}T_{muscle}$$

W : Weight of layer

T : Temperature of layer

Temperature Measurement

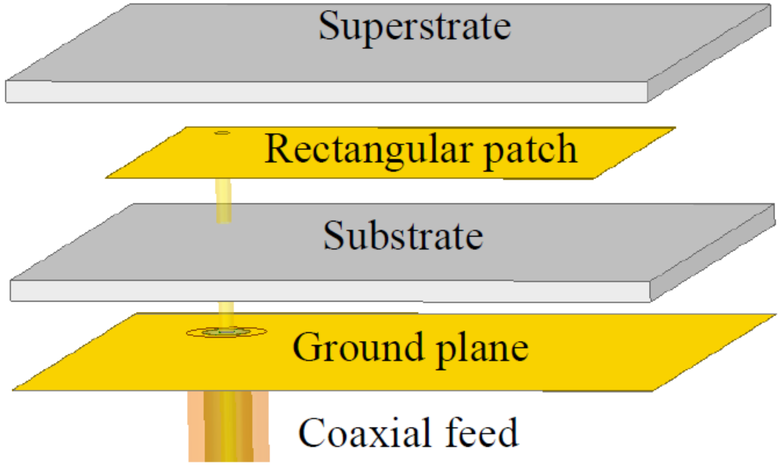
1.4 ~ 1.427 GHz : $kTB = -99.5\ dBm$
@ 27°C B= 27 MHz



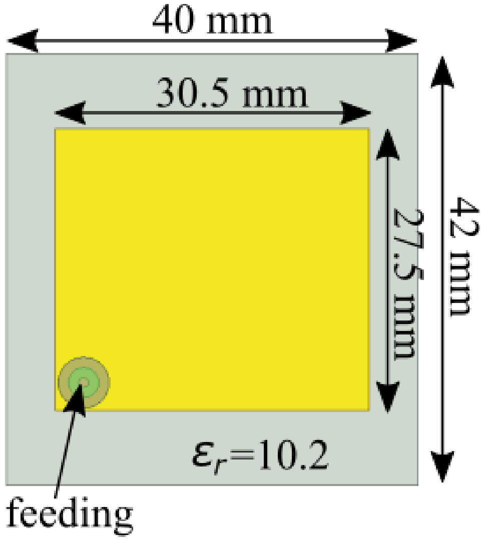
- Dicke radiometer connected to a phantom tissue stack of skin and muscle
- Switch and LNA implemented on a GaAs MMIC
- Output digitized and processed

Near-field Antenna Design

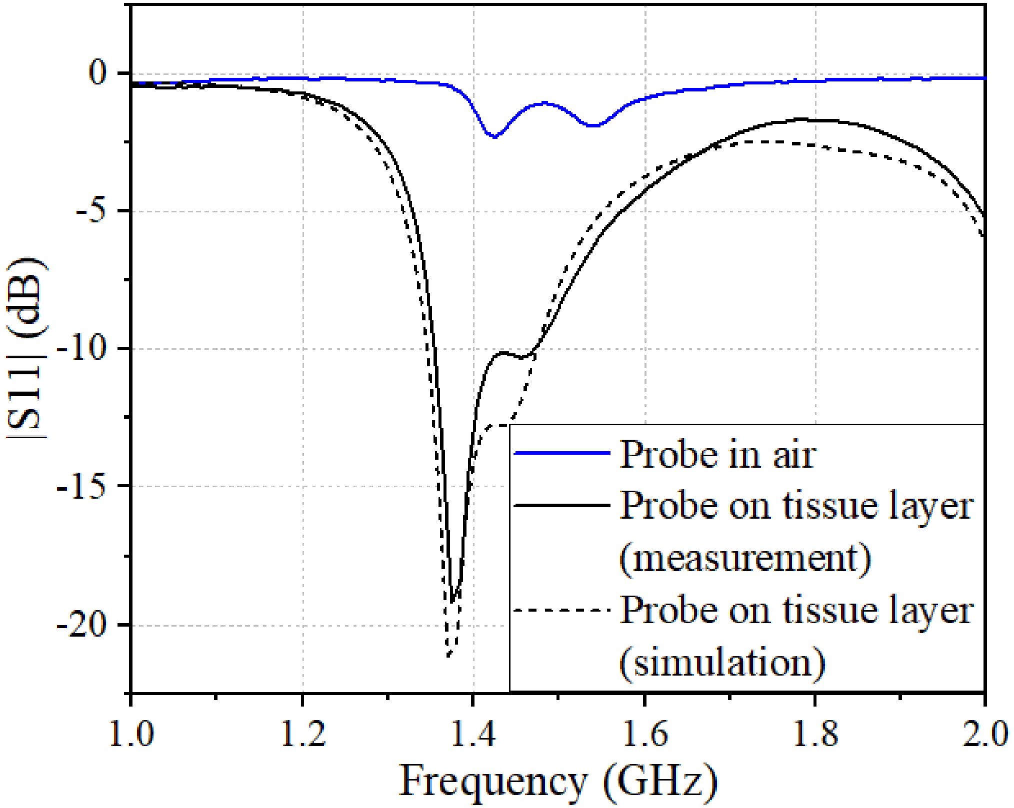
Cross-section



Top view



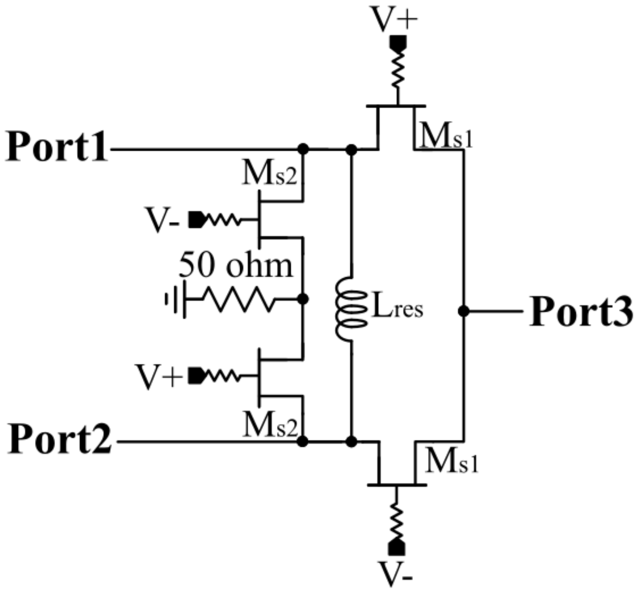
Reflection coefficient magnitude

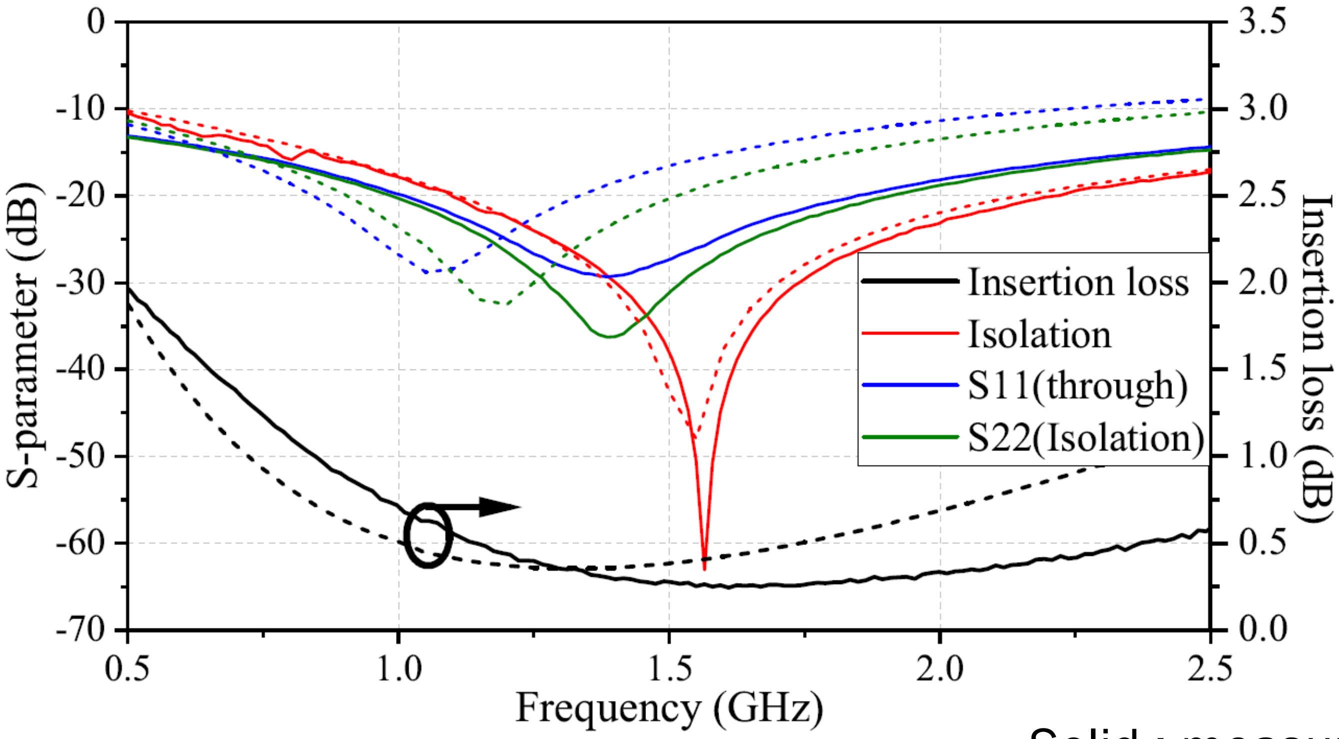


- Designed to match the tissue layers
- Rectangular patch topology

SPDT Switch Design

Schematic



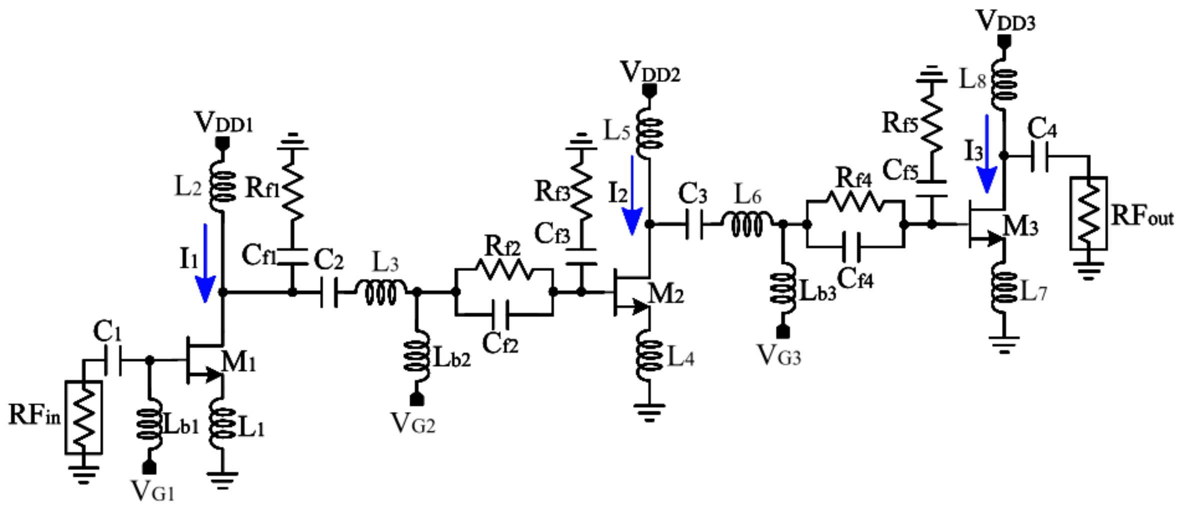


- Solid : measurement
- Dashed: simulation

- Shunt-series topology
- Inductor(L_{res}) to resonate the “OFF” capacitors of the transistors
- Insertion loss: 0.29 dB / Isolation: 30.8 dB @1.4 GHz

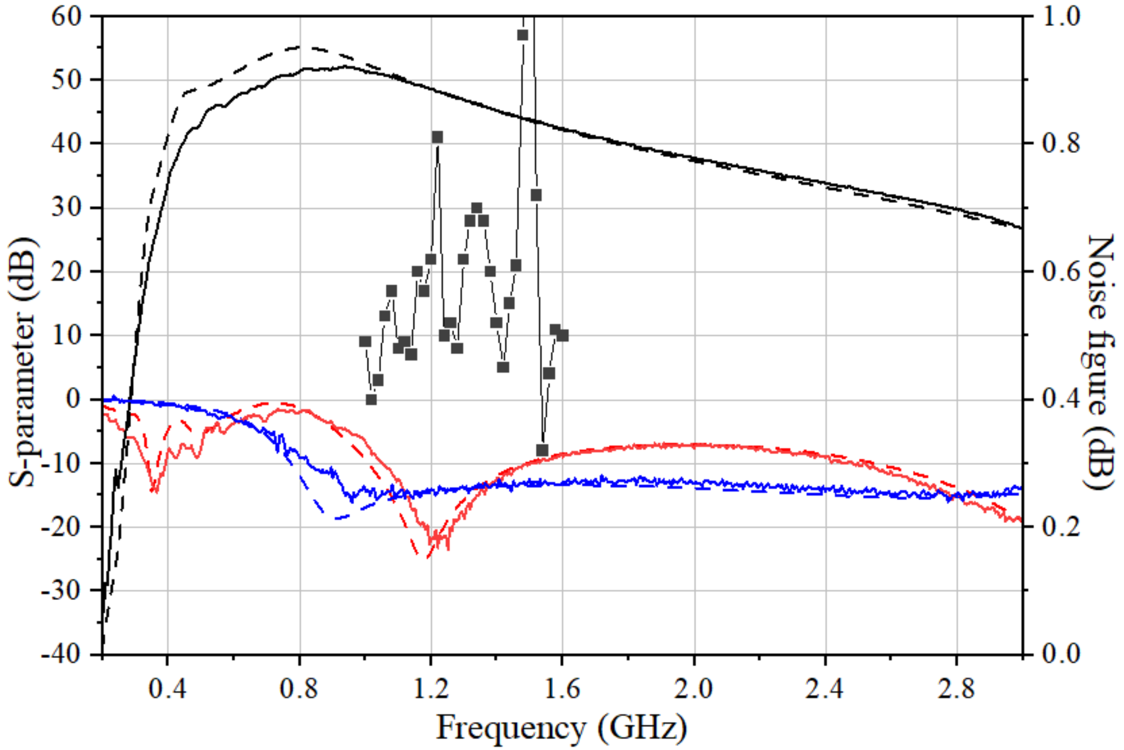
LNA Design

Schematic



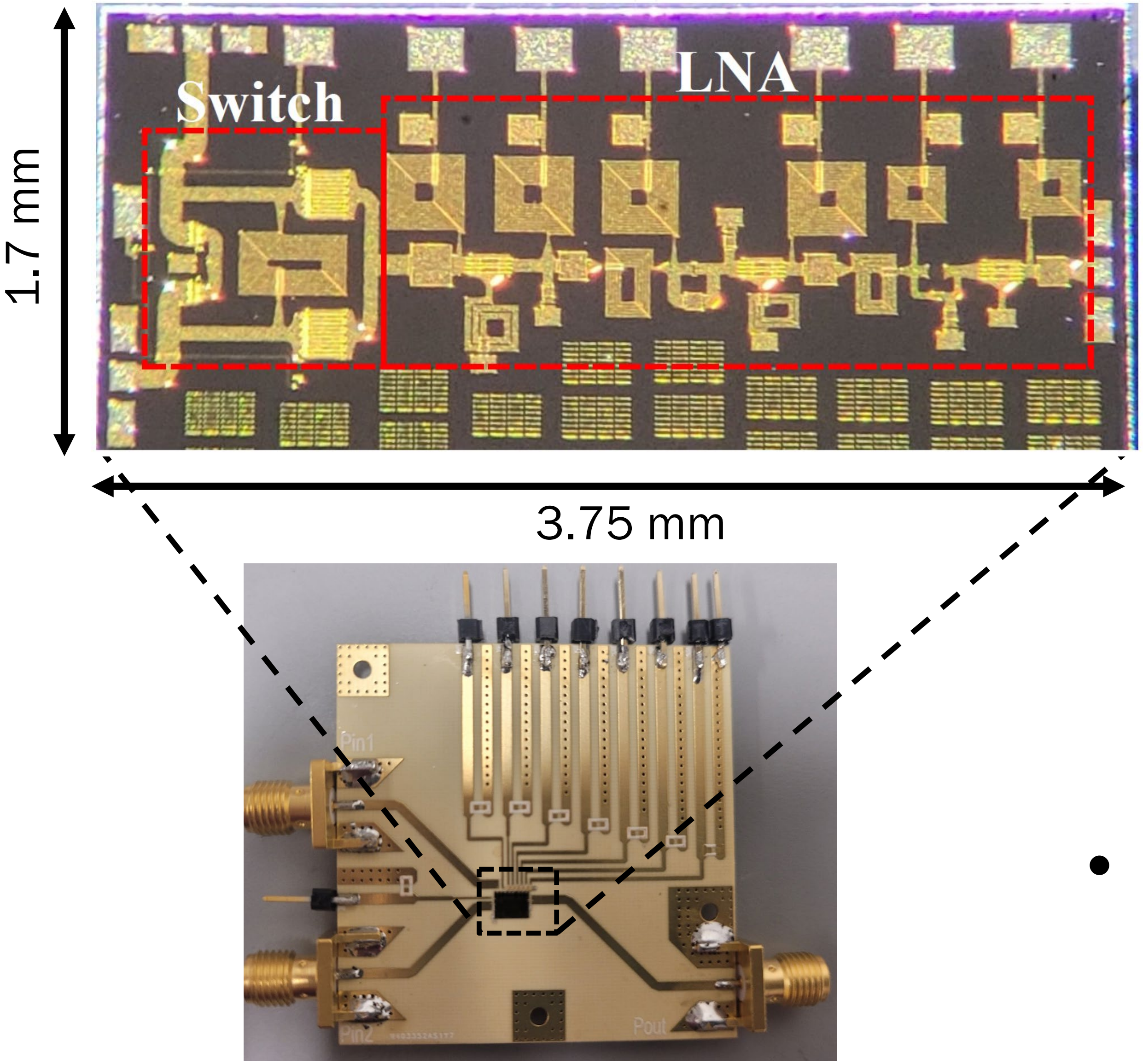
M_1=4 x 164 um	L_{b1}=21.6 nH	L_1=0.95 nH	L_5=21 nH	C_1=8 pF	$V_{DD1,2,3}$=2 V	I_1=16.4 mA
M_2=4 x 180 um	L_{b2}=21 nH	L_2=20 nH	L_6=1.2 nH	C_2=4 pF	V_{G1}=0.49 V	I_2=12.2 mA
M_3=4 x 132 um	L_{b3}=6.2 nH	L_3=4.7 nH	L_7=0.2 nH	C_3=5 pF	V_{G2}=0.47 V	I_3=13.6 mA
		L_4=1.3 nH	L_8=6.5 nH	C_4=1.5 pF	V_{G3}=0.48 V	

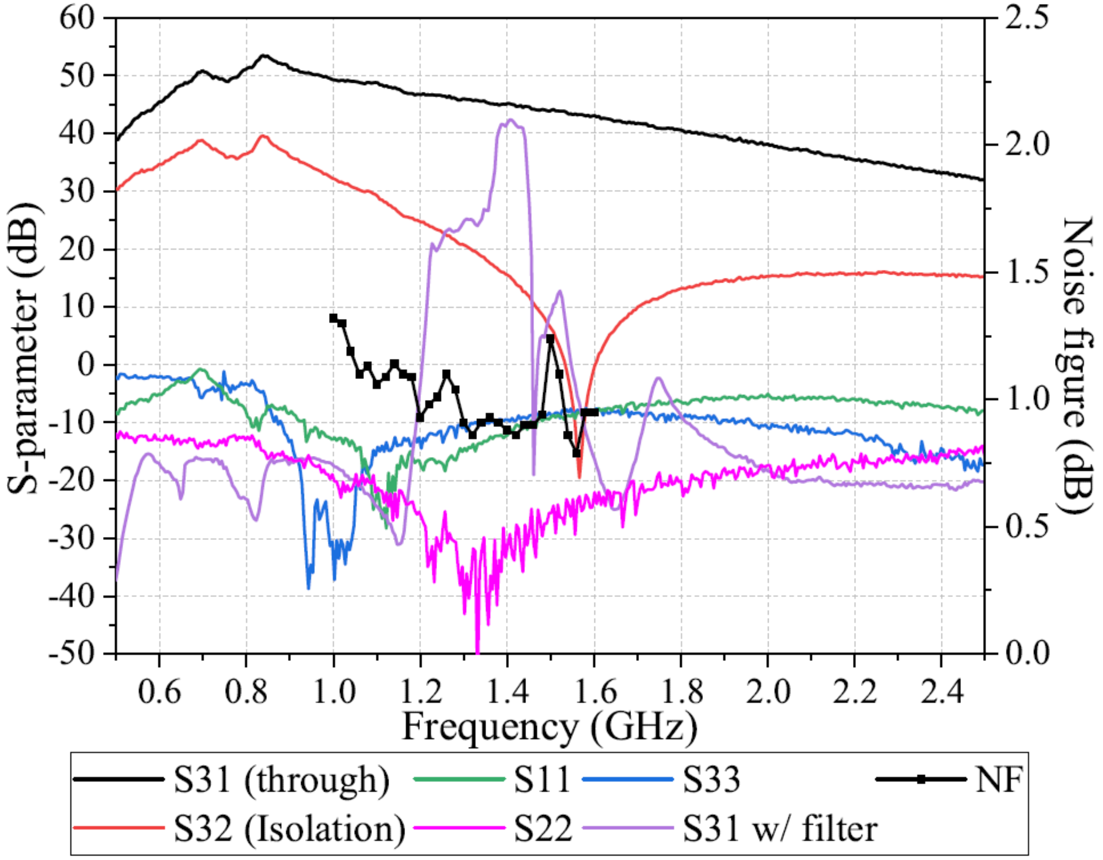
Measurement



- 3-stage common source amplifier
- Distributed filters for stability improvement
- Performance at 1.4 GHz: Gain: 45.2 dB/Noise figure: 0.52 dB

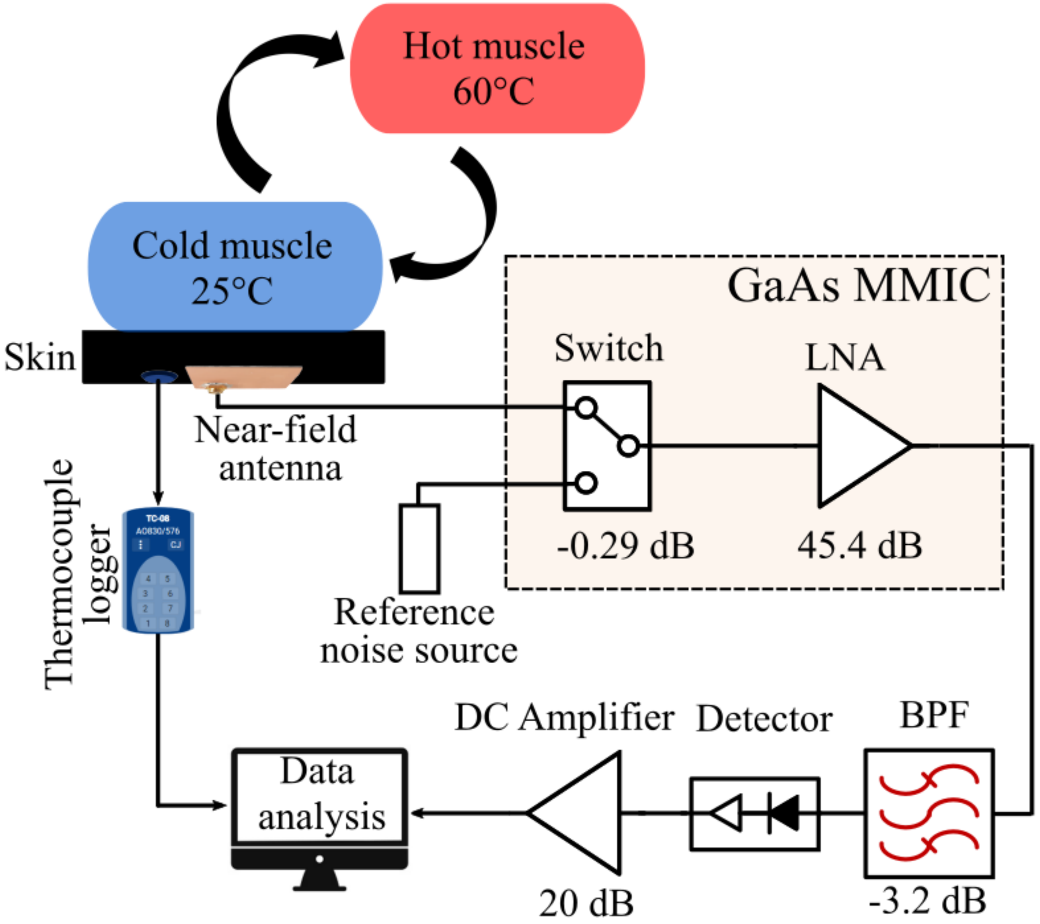
MMIC Implementation

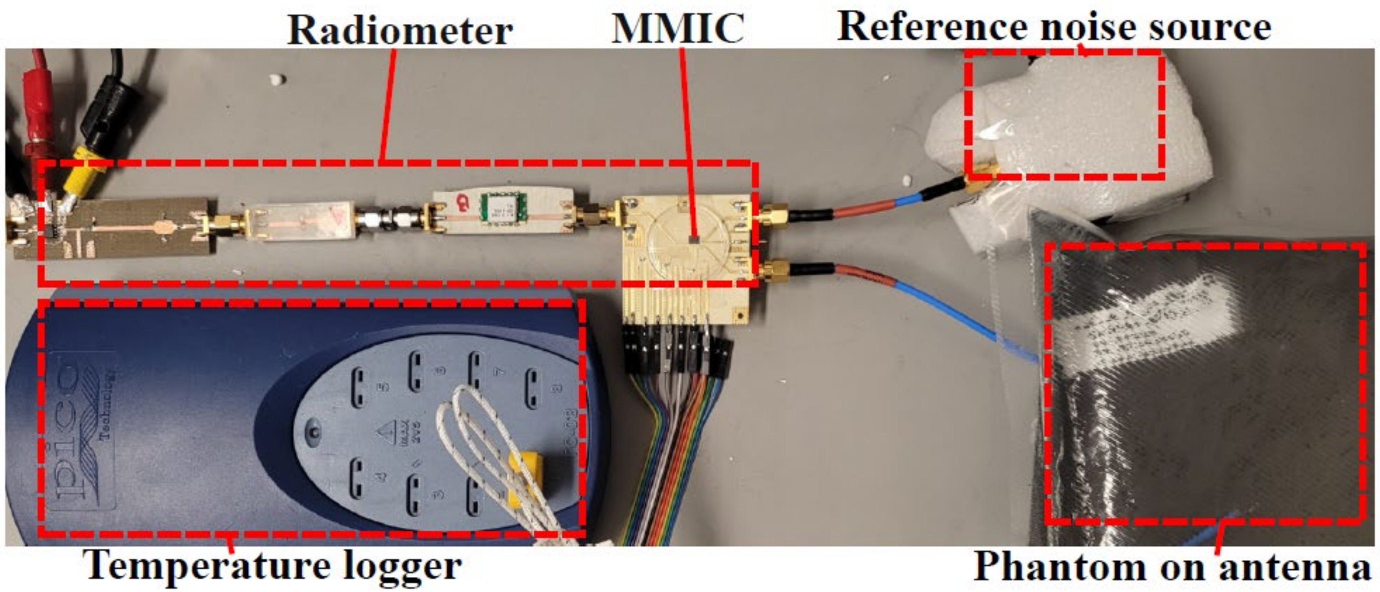




- Performance at 1.4 GHz
  - Gain: 45.1 dB / 41.9 dB w/ filters
  - Noise figure: 0.88 dB

Measurement Test Setup

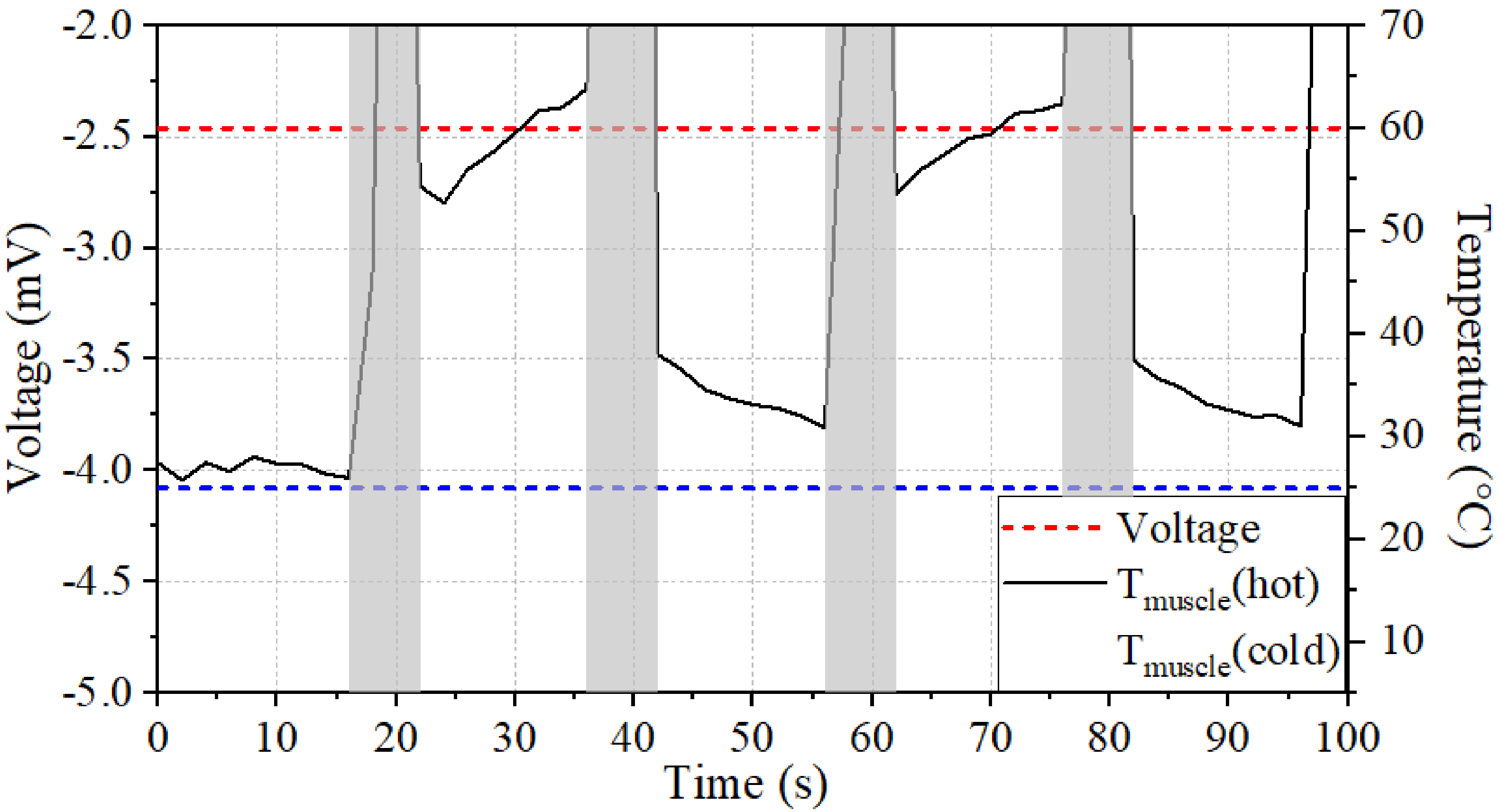




Phantom	Thickness (mm)	ε_r	δ (S/m)
Skin	2	28	0.82
Muscle	15	77.7	1.26

- Two muscle phantoms alternated on skin phantom

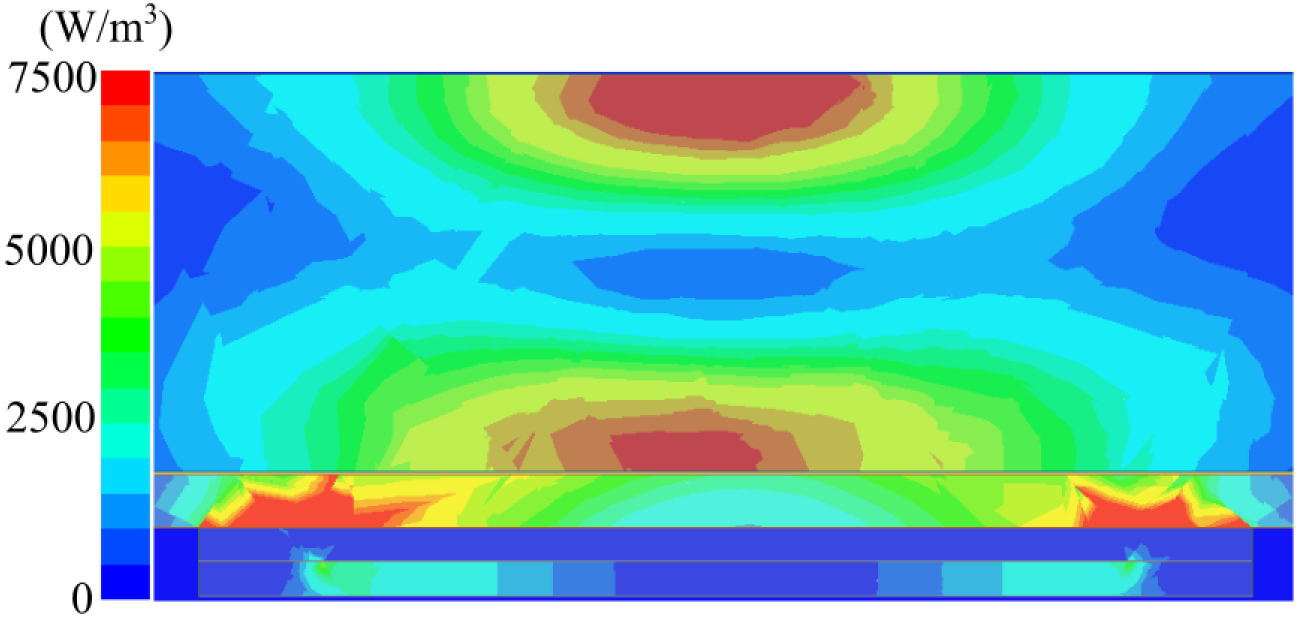
Temperature Measurement



- Two muscle phantoms alternated every 20 seconds

Temperature Measurement

Volume Joule loss of tissue phantom



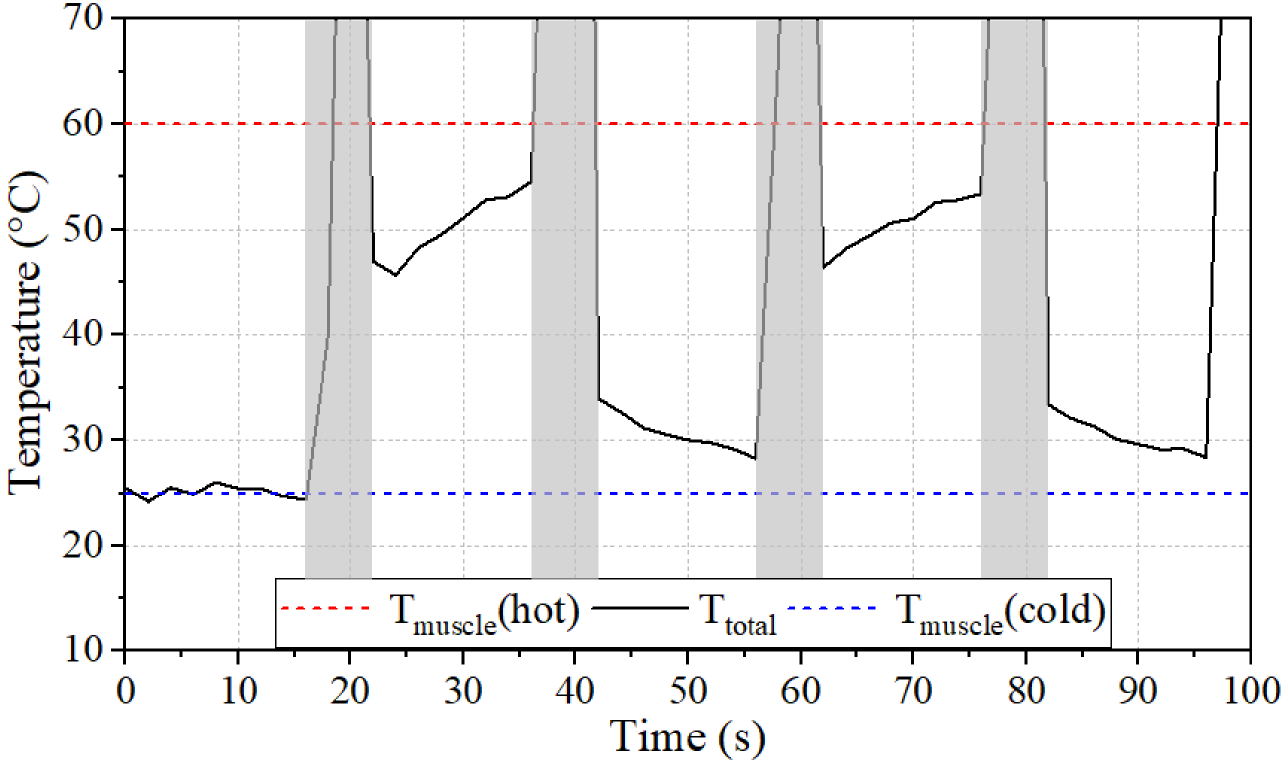
Weights from Joule loss

$$W_i = \frac{\int_{v_i} \rho_J}{\int_{v_{tot}} \rho_J}$$

W_{muscle} : 0.593
W_{skin} : 0.261
W_{probe} : 0.03

$$T_{total} = W_{skin} T_{skin} + W_{muscle} T_{muscle}$$

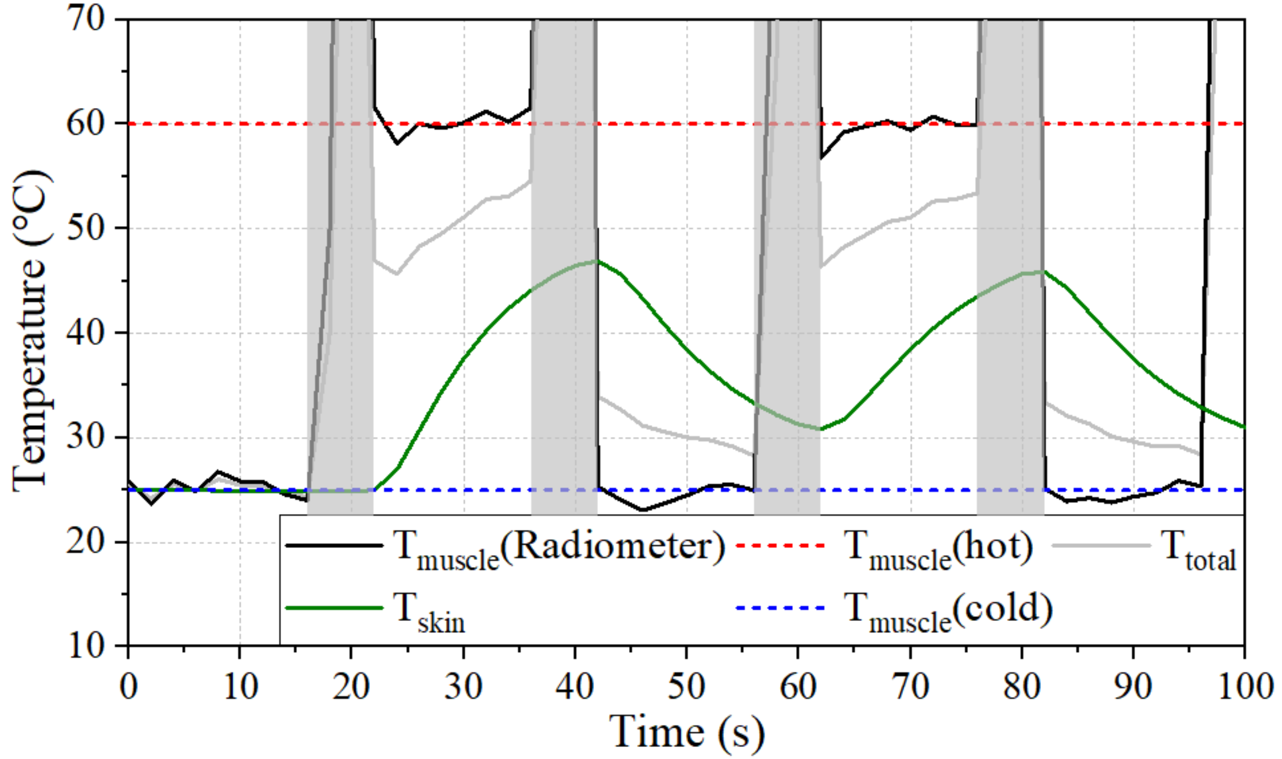
Temperature Estimation



$$T_{total} = W_{skin}T_{skin} + W_{muscle}T_{muscle}$$

- Skin temperature is calibrated to estimate muscle temperature
- Average error of 0.77 °C

Temperature Estimation

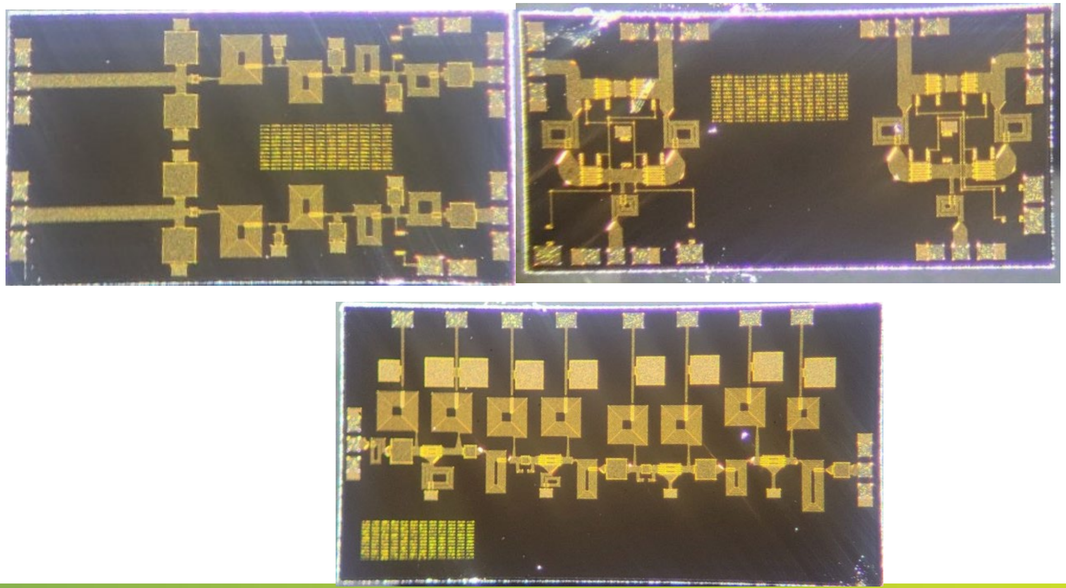


$$T_{total} = W_{skin}T_{skin} + W_{muscle}T_{muscle}$$

- Skin temperature is calibrated to estimate muscle temperature
- Average error of 0.77 °C

Conclusion

- Non-invasive internal body temperature measurement
  - 45 dB stable gain, 0.88 dB noise figure for Dicke MMIC
  - About 80 mW power consumption
  - Temperature measurement and estimation using 2-layer phantom stack
  - Average estimation error of 0.77 °C
- Future work
  - Further implementation to MMIC
  - Temperature measurement of multi-stack tissue layers



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[2] UCSF Health. (2020, October 7). Hyperthermia. ucsfhealth.org. Retrieved September 22, 2022, from https://www.ucsfhealth.org/treatments/hyperthermia

[3] Lack, L. C., Gradisar, M., Van Someren, E. J., Wright, H. R., & Lushington, K. (2008). The relationship between insomnia and body temperatures. Sleep medicine reviews, 12(4), 307-317.

[4] G. Galiana, R. T. Branca, E. R. Jenista, and W. S. Warren, “Accurate temperature imaging based on intermolecular coherence in magnetic resonance,” Science, vol. 322, no. 5900. 2008. https://doi.org/10.1126/science.1163242.

[5] Riddhi, & *, N. (2015, August 25). *Pill measures body temperature*. Health Tech Insider. Retrieved January 17, 2023, from https://healthtechinsider.com/2015/08/25/ingestible-heat-monitor-bodycap/

Thank you ☺
Questions?