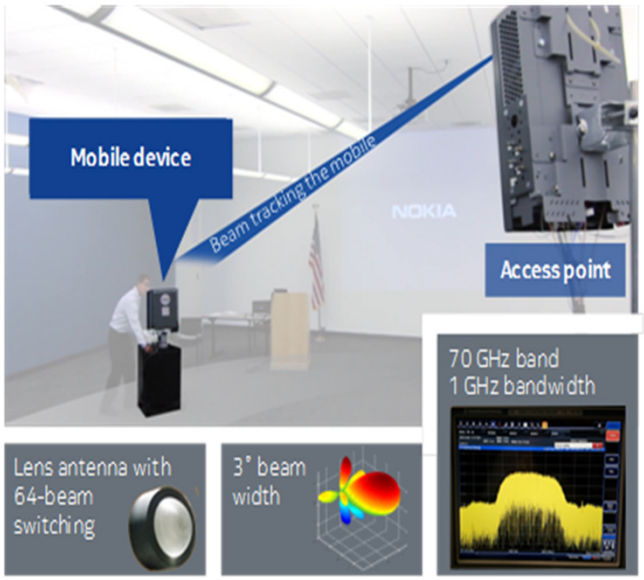
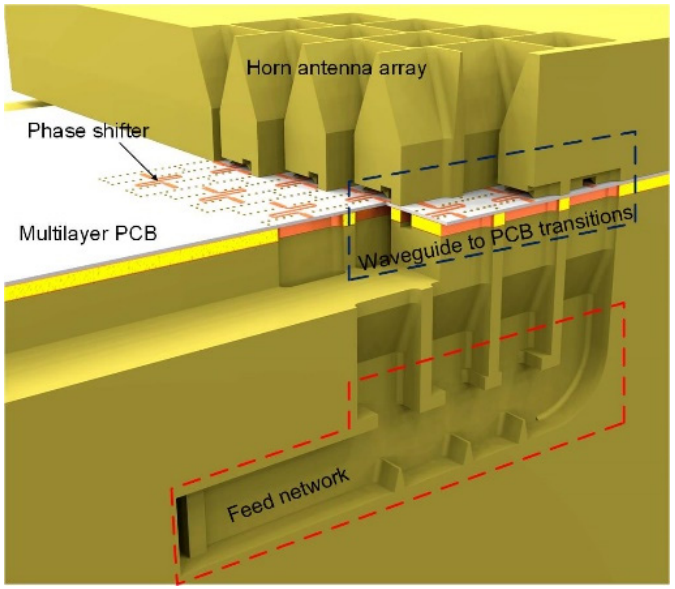
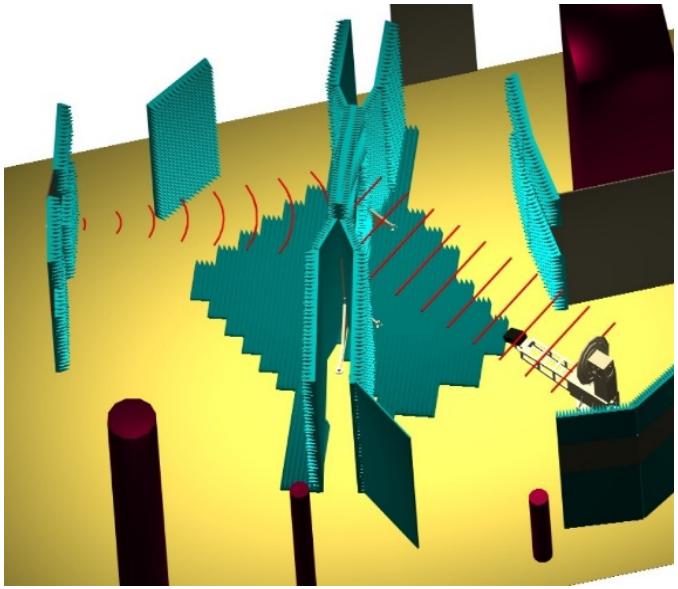
Ready for 5G and Beyond:

Aalto University has 3+ decades of research on mm-wave and THz antennas, circuits, and systems







- **Antennas (e.g. for Nokia E-band 5G demonstrators) and antenna measurement techniques**

Aalto People

Kari Halonen

Jussi Ryynänen

Katsuyuki Haneda

Antti Räisänen

postdocs

Zachary Taylor

Ville Viikari

Riku Jäntti

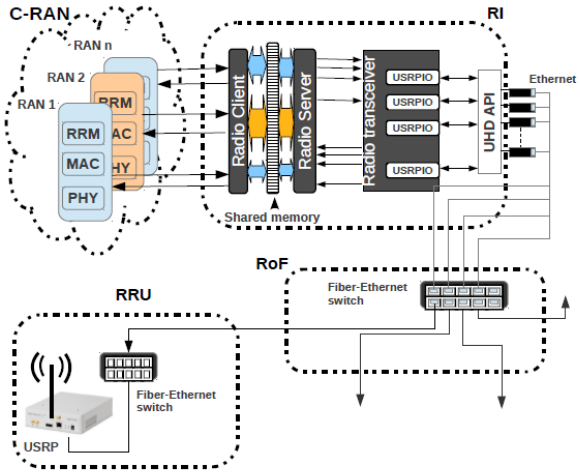
Olav Tirkkonen

Masters/PhD students

- Interdisciplinary Group
  - Dept. of Electronics and Nanoengineering
  - Dept. of Communications and Networking

Software defined radio support for THz experimentation

C-RAN architecture

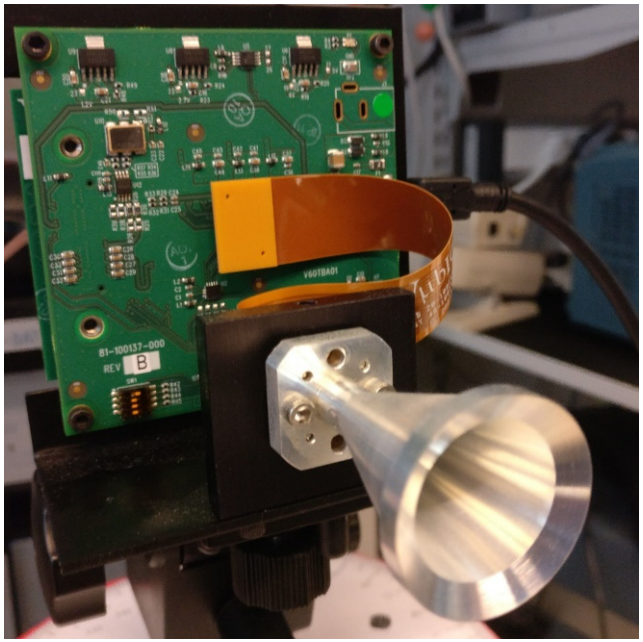


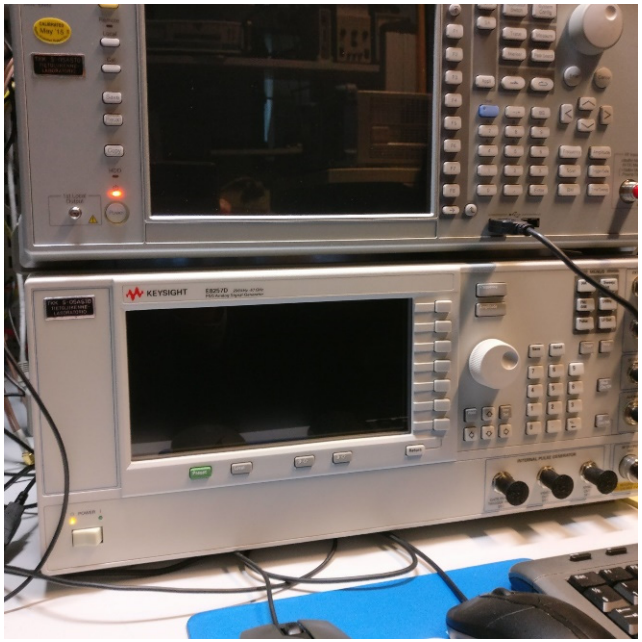
Remote radio units

Lamppost mounted 5G gNB TRP

- Department of Communications and Networking has a long track-record in developing full protocol stacks
- Base band processing implementation in C++
  - TD-LTE (Rel. 8) PHY + RLC
  - NB-IoT (Rel. 13) standalone mode
    full base station implementation
  - NR (Rel. 15) PHY + RLC
- Cloud based Radio Access Networks (C-RAN):
  - Soft-real-time based band processing in standard Linux computing environments
- Ethernet front-haul
- Software defined radio units

Software defined radio support for THz experimentation





- Ultra-wideband experimentations
  - Transceiver algorithm implementations (C++, Matlab)
  - Waveform generation up to 6 GHz bandwidth with signal generator
  - IF generation with signal generator up to 70 GHz
  - Signal generator with 6 GHz bandwidth can be used as a receiver

Publications on full stack development and experimentation

1. N. Malm, L. Zhou, E. Menta, K. Ruttik, R. Jäntti, O. Tirkkonen, M. Costa, and K. Leppänen, "User Localization Enabled Ultra-dense Network Testbed," 2018 IEEE 5G World Forum (5GWF), Santa Clara, California, June 9-11, 2018.

2. Y. Beyene, R. Jäntti, O. Tirkkonen, K. Ruttik, S. Iraji, A. Larmo, T. Tirronen, and J. Torsner, "NB-IoT Technology Overview and Experience from Cloud-RAN Implementation", IEEE Wireless Communications Magazine, 2017.

3. Y. Beyene, R. Jäntti, K. Ruttik and S. Iraji, "On the Performance of Narrow-Band Internet of Things (NB-IoT), In. Prof. IEEE WCNC 2017, San Francisco, March 2017.

4. J. Kerttula, Y. Beyene, N. Malm, L. Zhou, K. Ruttik, O. Tirkkonen and **R. Jäntti**, " Spectrum Sharing in D2D Enabled HetNet", Demo, In Proc. IEEE DySPAN 2015, Stockholm, Sweden, September 29 – October 2, 2015.

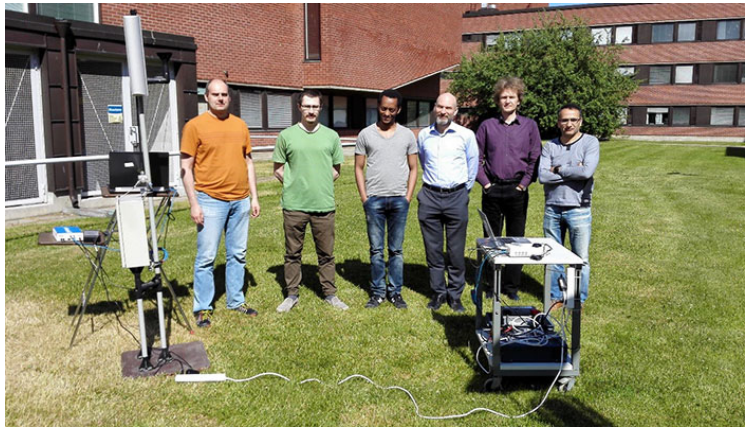
5. L. Zhou, J. Kertula, N. Malm, Y. Beyene, K. Ruttik, O. Tirkkonen and R. Jäntti, " Creating Secondary Spectrum Usage Opportunity for D2D Communication with Interference Cancellation", Demo, In Proc. IEEE DySPAN 2015, Stockholm, Sweden, September 29 – October 2, 2015.

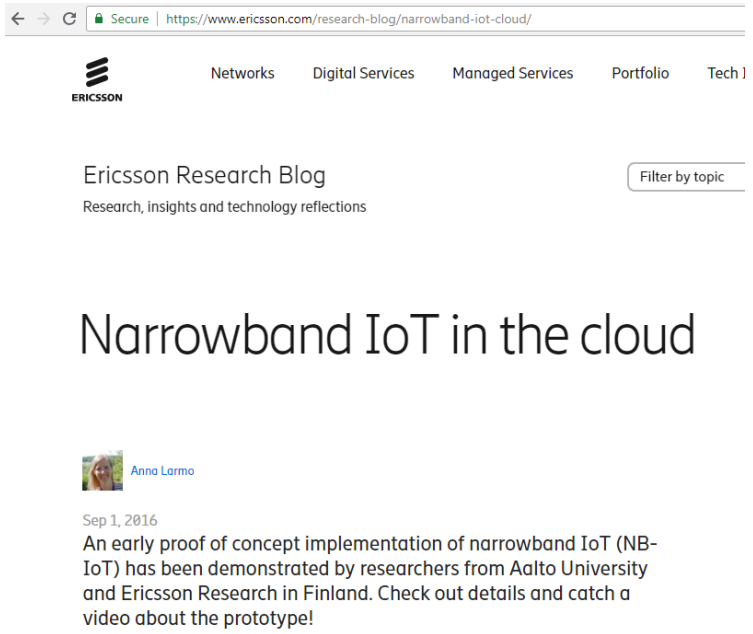
6. Y. Beyene, N. Malm, J. Kertula, L. Zhou, K. Ruttik, R. Jäntti, O. Tirkkonen and C. Bockelmann, " Spectrum Sharing for MTC Devices in LTE", Demo, In Proc. IEEE DySPAN 2015, Stockholm, Sweden, September 29 – October 2, 2015.

7. Y. Beyene, R. Jäntti, and K. Ruttik, "Cloud-RAN Architecture for Indoor DAS," IEEE Access, Vol 2, 2014.

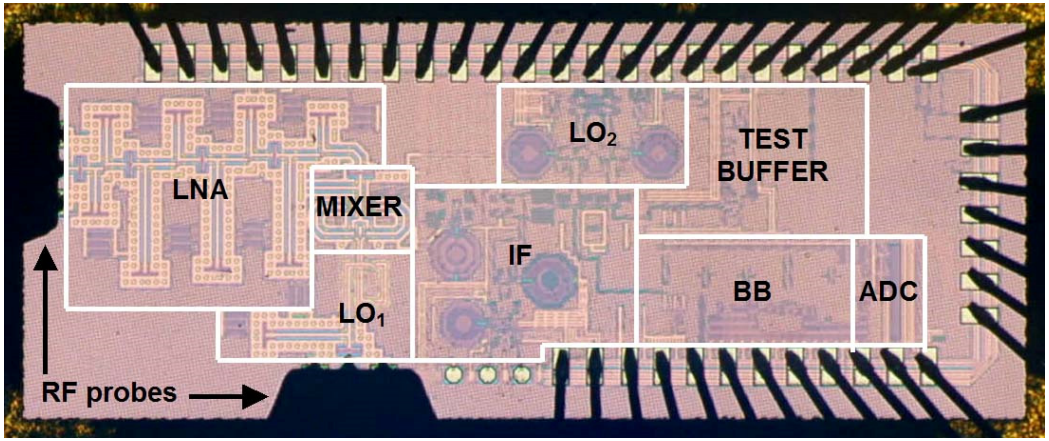
8. J. Kerttula, N. Malm, K. Ruttik, R. Jäntti, and O. Tirkkonen, "Implementing TD-LTE as software defined radio in general purpose processor," In Proc. ACM Annual Conference of the Special Interest Group on Data Communication SIGCOMM 2014, Chigago, USA, August 17-22, 2014.

9. K. Ruttik, N. Malm, O. Tirkkonen and R. Jäntti, "Soft-real-time Cloud based Radio Access Networks," US Provisional applied (application number 6202604)





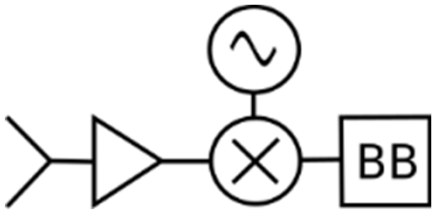
Integrated circuits for Sub-THz bands



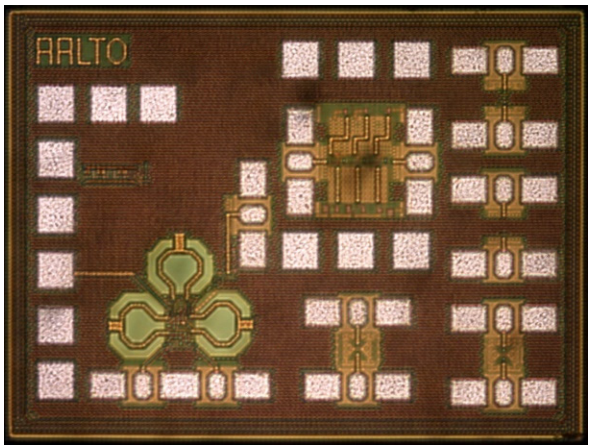
First full 60GHz CMOS receiver with on chip ADC already published in 2009

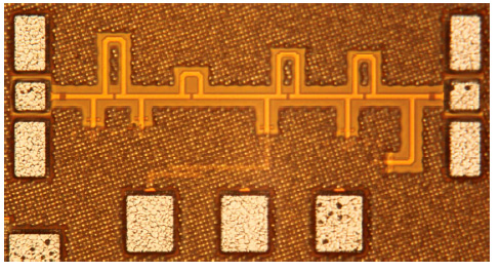
- 20 years of MMIC development for communications, space and radar
- Current focus
  - Develop digitally assisted array MMIC systems up to 200GHz
  - Push tech. boundaries towards THZ bands with individual building blocks
  - Develop antenna-IC codesign environment
- Utilization of nanometer CMOS and BiCMOS technologies

Recent examples of MMIC development

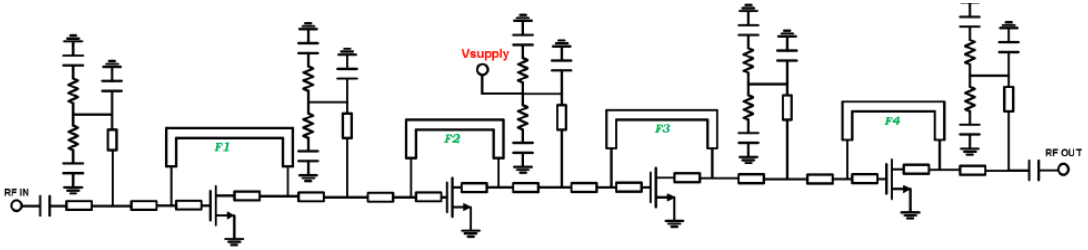


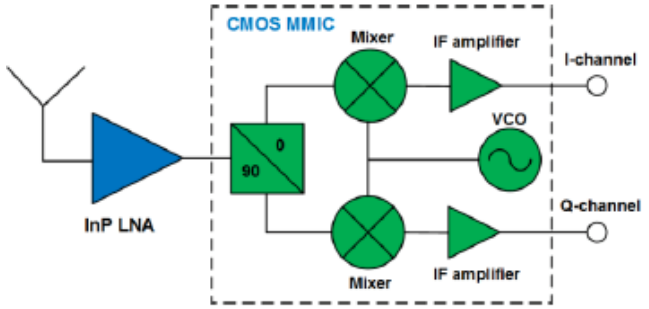
140-GHz Radiometer



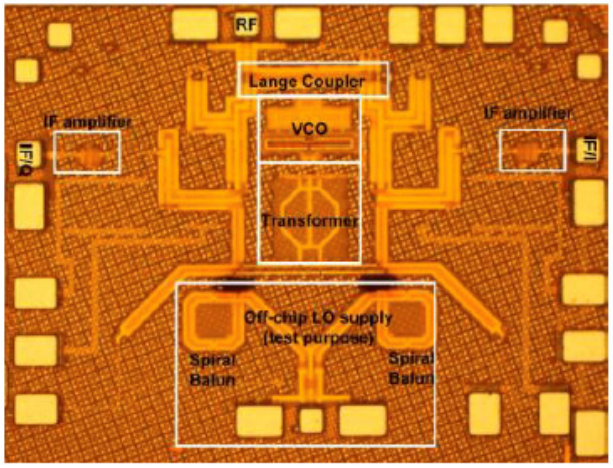


0.325 THz CMOS amplifier





180-GHz CMOS Down-converter MMIC for Atmospheric Remote Sensing

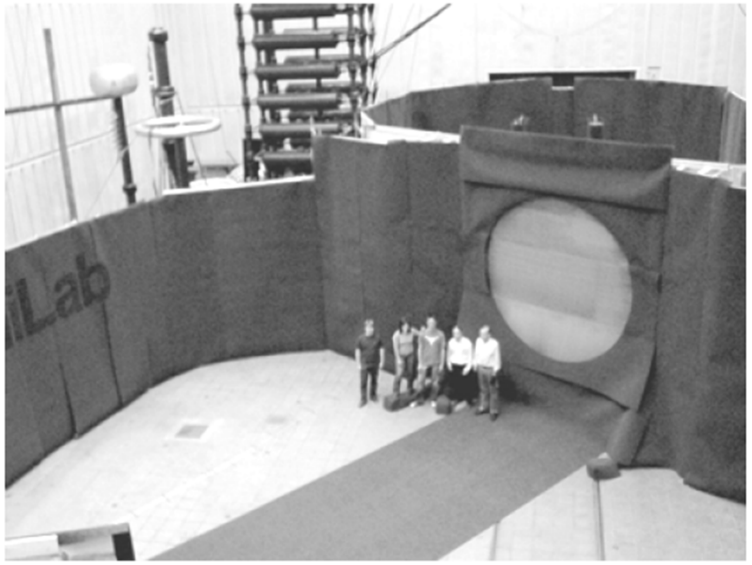


Radio channel modelling / standardisation

- Successful contribution to the white paper ‘5G Channel Model for bands up to 100 GHz’ allowed us to kick-start 5G wireless standardisation activities in 3GPP (representatives of wireless equipment vendors and operators across the world).

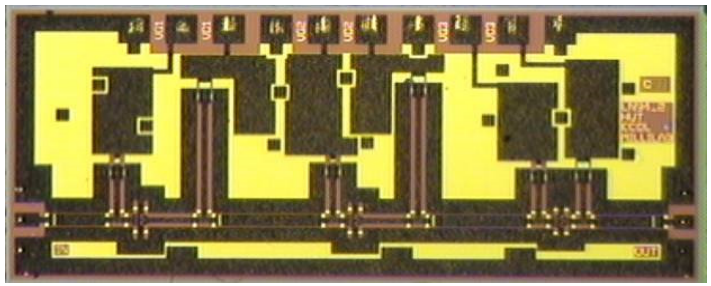
- Successful leadership in a working group of radio channels in the European COST Action IRACON, led to an input document to the ITU SG3 about various radio propagation models at mm-wave frequencies.

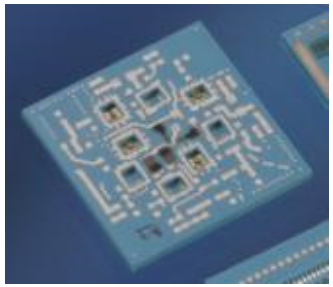
Millimetre-wave Laboratory of Finland - MilliLab



- A Joint Laboratory, established 1995
  - **VTT** Technical Research Centre of Finland
  - **Aalto** University, School of Electrical Engineering
- An ESA External Laboratory on Millimetre-wave technology (since 1995)
  - Mission: *assist European* space *industry* in meeting the demands of future mm-wave missions
- Combines the benefits of the two mother organizations:
  - **Aalto**: Strong academic competence
  - **VTT**: Competence closer to industry, established processes, experts, facilities

MilliLab key Services and capabilities



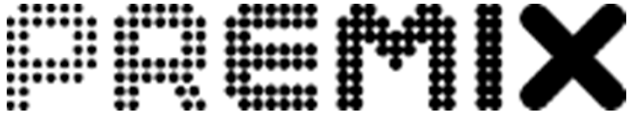


- Millimeter wave test and measurement services
  - S-parameters, spectrum measurements, noise figure and noise parameters. On-wafer measurements up to 500 GHz and with waveguides up to 1.1 THz
  - Antenna measurements: near-field with a planar scanner up to 1 THz
- Laboratories and equipment for space qualification
- Reliability testing:
  - Temperature step stress tests, RF step stress tests, DC step stress tests, RF life tests, DC life tests, Temperature cycling, High humidity high temperature tests.
- Design and development services for millimeter wave components, circuits, modules, sub-systems

MilliLab dissertations in 2010-2018

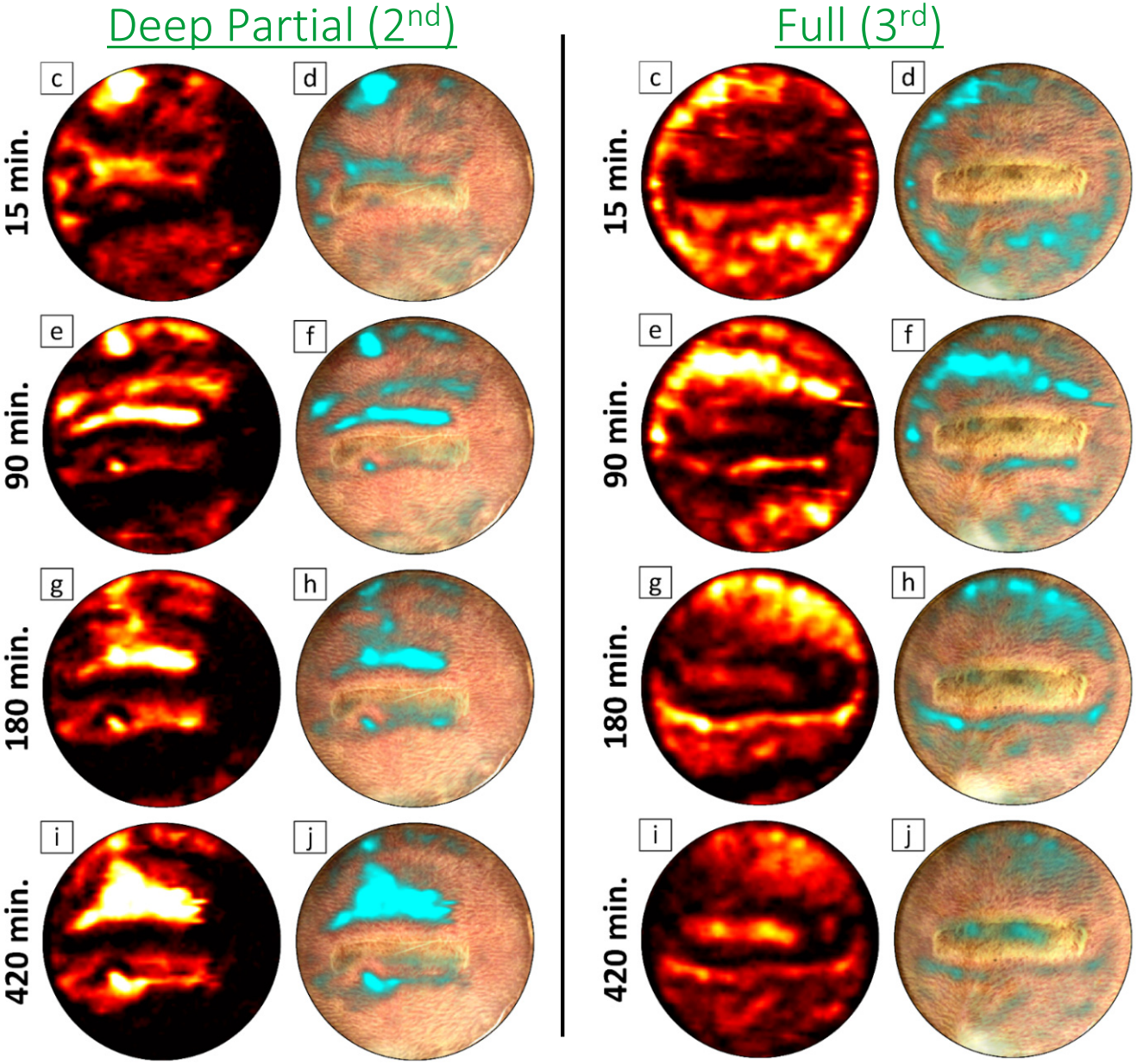
Mikko Varonen	Design and characterization of monolithic millimeter-wave active and passive components, **2010**
Patrik Pousi	Active and passive dielectric rod waveguide components for millimetre wavelengths, **2010**
Dmitri Chicherin	Studies on microelectromechanically tuneable high-impedance surface for millimetre wave beam steering, **2011**
Tero Kiuru	Characterization, modelling, and design for applications of waveguide impedance tuners and Schottky diodes at mm-wavelengths, **2011**
Mikko Kyrö	Radio wave propagation and antennas for millimeter wave communications, **2013**
Aki Karttunen	Millimetre and submillimetre wave antenna design using ray tracing, **2013**
Aleksi Tamminen	Developments in imaging at millimeter and submillimeter wavelengths, **2013**
Mikko Kärkkäinen	Design and characterization of monolithic millimeter-wave integrated circuits for receiver front-ends, **2014**
Krista Dahlberg	Development of on-wafer calibration methods and planar Schottky diode characterisation at THz frequencies, **2014**
Tomas Zvolensky	Periodic transmission lines for leaky-wave antenna applications at millimeter wavelengths, **2014**
Zhou Du	Characterization of antennas and quasioptical components through simulations and measurements, **2015**
Andrey Generalov	Dielectric rod waveguide components at sub-THz frequencies, **2015**
Vasilii Semkin	Reconfigurable antennas and radio wave propagation at millimeter-wave frequencies, **2016**
Mikko Kantanen	Low-noise monolithic millimeter-wave integrated circuits and a radiometric imaging system, **2017**
Irina Nefedova	Electrical and optical properties of carbon nanotube and silver nanowire layers for low-THz applications, **2017**
Subash Khanal	Chracterisation of Schottky diodes and dielectric materials for millimeter wave and THz applications, **2017**
Ali Vahdati	Design and characterisation of monolithic millimetre-wave integrated circuits for phased-array transmitter front-end, **2017**
Dristy Parveg	CMOS radio front-end circuit blocks for millimeter-wave communications and atmospheric remote sensing receivers, **2018**

Industrial collaboration



- Nokia
- ESA
- Huawei
- HiSilicon
- SAAB
- Sasken
- Qualcomm
- DA-Design
- Pulse
- Nordic Semiconductor
- VTT
- Finnish Defence Force
- AAC Technologies
- Optenni
- Cojot
- Premix
- Keysight
- ETS-Lindgren

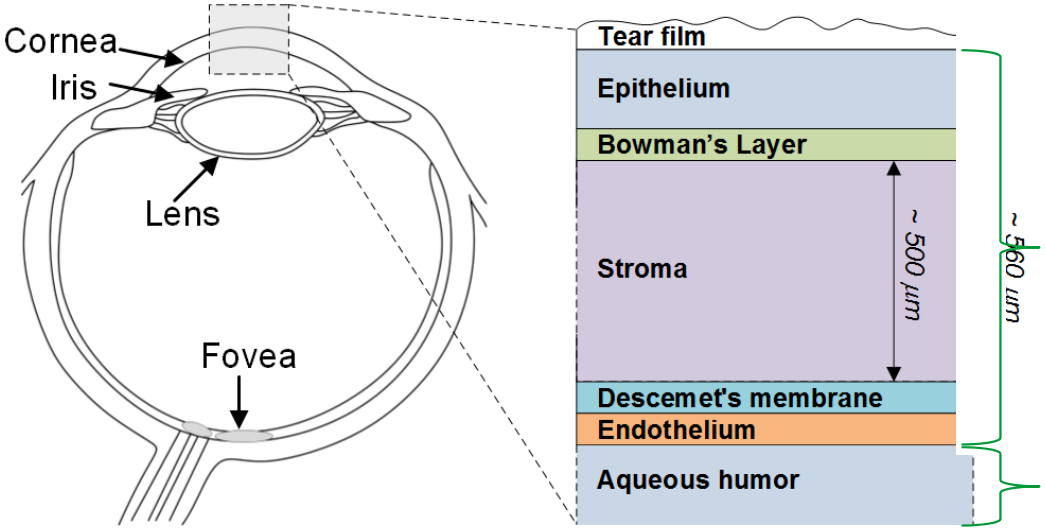
Visualizing spatiotemporal variation in burn edema



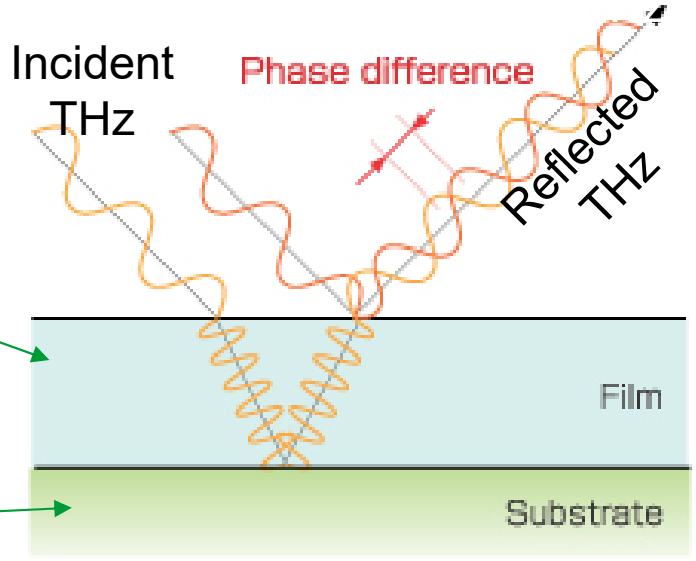
- Visualize the build up of tissue edema in response to burn injury
- Track water through space and time using THz imaging
- THz derived imaging features vary based on burn severity
- Early severity detection

Corneal water content char. with thin film metrology

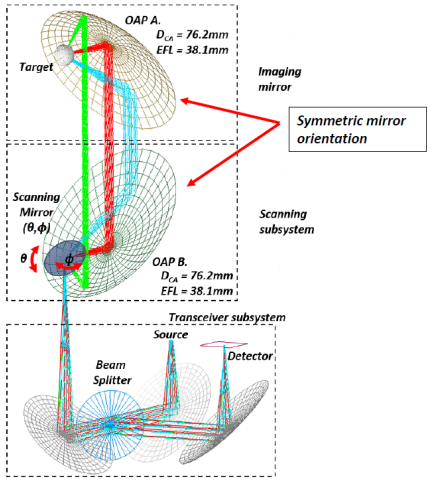
Cornea

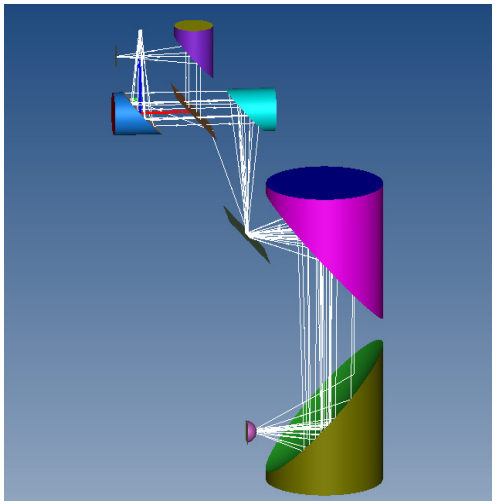


Frequency domain Ellipsometry

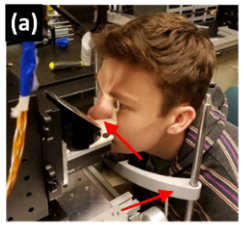


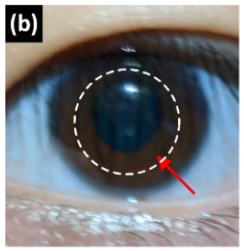
Optial System Design

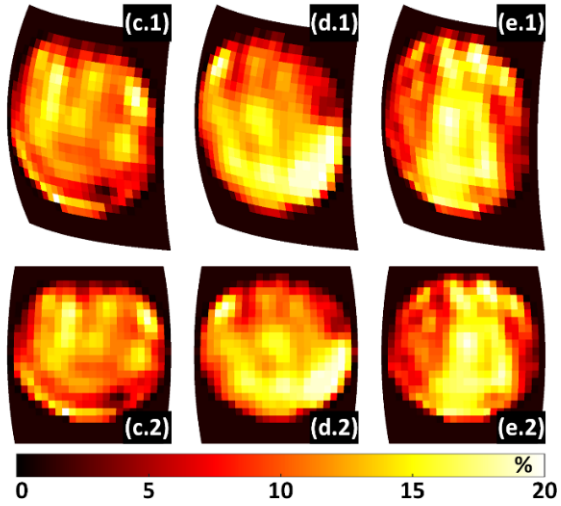




Human trials







Biomedical sensing publications

1. N. Bajwa, S. Sung, D. B. Ennis, M. C. Fishbein, B. Nowroozi, D. Ruan, A. Maccabi, J. Alger, M. A. S. John, W. S. Grundfest, and Z. D. Taylor, "Terahertz Imaging of Cutaneous Edema: Correlation with Magnetic Resonance Imaging in Burn Wounds," *IEEE Transactions on Biomedical Engineering,* vol. PP, pp. 1-1, 2017.
2. N. Bajwa, J. Au, R. Jarrahy, S. Sung, M. C. Fishbein, D. Riopelle, D. B. Ennis, T. Aghaloo, M. A. St. John, W. S. Grundfest, and Z. D. Taylor, "Non-invasive terahertz imaging of tissue water content for flap viability assessment," *Biomedical Optics Express,* vol. 8, pp. 460-474, 2017/01/01 2017.
3. Z. D. Taylor, J. Garritano, S. Shijun, N. Bajwa, D. B. Bennett, B. Nowroozi, P. Tewari, J. W. Sayre, J. P. Hubschman, S. X. Deng, E. R. Brown, and W. S. Grundfest, "THz and mm-Wave Sensing of Corneal Tissue Water Content: In Vivo Sensing and Imaging Results," *Terahertz Science and Technology, IEEE Transactions on,* vol. 5, pp. 184-196, 2015.
4. Z. D. Taylor, J. Garritano, S. Sung, N. Bajwa, D. B. Bennett, B. Nowroozi, P. Tewari, J. Sayre, J. P. Hubschman, S. Deng, E. R. Brown, and W. S. Grundfest, "THz and mm-Wave Sensing of Corneal Tissue Water Content: Electromagnetic Modeling and Analysis," *Terahertz Science and Technology, IEEE Transactions on,* vol. 5, pp. 170-183, 2015.
5. Z. D. Taylor, R. S. Singh, D. B. Bennett, P. Tewari, C. P. Kealey, N. Bajwa, M. O. Culjat, A. Stojadinovic, L. Hua, J. P. Hubschman, E. R. Brown, and W. S. Grundfest, "THz Medical Imaging: in vivo Hydration Sensing," *Terahertz Science and Technology, IEEE Transactions on,* vol. 1, pp. 201-219, 2011.
6. P. Tewari, C. P. Kealey, D. B. Bennett, N. Bajwa, K. S. Barnett, R. S. Singh, M. O. Culjat, A. Stojadinovic, W. S. Grundfest, and Z. D. Taylor, "In vivo terahertz imaging of rat skin burns," *Journal of Biomedical Optics,* vol. 17, pp. 040503-3, 2012.