Background and Mission

The Circuits and Systems group consists of ~25 researchers working at the Electronics Laboratory of the Department of Electrical Engineering at the University of Oulu. Its main activity is in the field of electronic and optoelectronic circuit and system design. The main interest of the group is devoted to certain novel devices, circuit topologies and functional units, although the group is also interested in applications, especially in the field of electronic/optoelectronic measurements and telecommunications.

The main research fields are:

- time-to-digital converters and timing circuits
- generation and detection of powerful and high-speed electrical and optical pulses/transients, and the study of breakdown phenomena in semiconductors in general
- development of pulsed time-of-flight laser range finding and time-gated Raman spectrometer technologies, especially for industrial applications
- radio telecommunications, including linearization of power amplifiers, AD/DA conversion and baseband blocks, frequency synthesis.

Part of the group activities belong to the Center of Excellence in Laser Scanning Research (funded by the Academy of Finland, 2014-2019, http://www.fgi.fi/coelasr/). Also, a FiDiPro Research Fellow Dr. Vassil Palankovski has joined the group. This 3-year position is funded by TEKES.

Scientific Progress

In the following, some details and results of the work of the group are given in selected important research fields.

Time-to-Digital Converters

A Wide Range, High Precision CMOS TDC Based on Switched-Frequency Ring Oscillators

A two-stage TDC has been developed in 0.35 µm CMOS process. The TDC achieves a single-shot precision of 4.2 ps (rms) with a measurement range of 327 µs. A coarse time quantization is done by a reference clock counter. The quantization error of the reference clock counter is then measured by two interpolators. These interpolators are based on a cyclic/algorithmic approach, thus they can achieve very high resolution. In each cycle, the time residue is quantized by a ring oscillator counter. The quantization error of the ring oscillator is then amplified by switching the frequency of the ring oscillator. The following amplified time residue is then measured again by the ring oscillator counter. This procedure continues as long as necessary to achieve the desired resolution.

Figure 1 shows the measured single-shot precision, when the input time interval is swept over a reference clock period. The average precision without INL compensation is about 4.2 ps. The interpolators provide a resolution of 0.61 ps, although the effective resolution is slightly worsened due to nonlinearity. Figure 2 shows the measured DNL and INL of each interpolator.

A digital calibration scheme ensures that high accuracy and high precision is retained in various operating conditions as shown in Figure 3. The calibration algorithm is based on modulating the time residues with a pseudo-random bit sequence, which enables the extraction of the required parameters by a simple correlation method. A die photo of the TDC is shown in Figure 4. The PCB designed for testing the TDC is shown in Figure 5.

Figure 1. Single-shot precision of the TDC when input time interval is swept over a reference clock period.
Figure 2. DNL and INL of the Start/Stop channel interpolators.

Figure 3. Average time interval and single-shot precision over a temperature range of -30 °C to 70 °C.

Figure 4. Die photo of the TDC.

Time-to-Digital Converter based on Time Domain Successive Approximation Interpolation

The proposed time-to-digital converter (TDC) aims at adjustable sub-ps-level resolution with high linearity in the ms-level dynamic range. The 13 bit TDC achieves a single-shot precision of 2.9 ps (rms) and 1.5 ps (rms) with INL-LUT compensation.

To achieve sub-ps-level resolution with cyclic time domain successive approximation (CTDSA) within a clock cycle, the propagation delay difference is implemented by digitally controlling both the unit load capacitors and the discharge current of the load capacitance. The TDC uses only a CTDSA as an interpolator with a 5 ns dynamic range within a clock cycle for sub-ps-level resolution and a counter for ms-level dynamic range without a DLL. A die photo of the TDC is shown in Figure 6. The measured single-shot precision σ-value and INL-LUT compensated precision are shown in Figure 7.

Figure 5. Photo of the TDC’s test PCB.

Figure 6. Die photo of the TDC.
Figure 7. Measured single-shot precision σ-value with and without INL-LUT correction.

Time-to-Digital Converter (TDC) Based on Startable Ring Oscillators (SRO) and Successive Approximation

The operating principle in this TDC revolves around startable ring oscillators (SRO). SROs are used as coarse interpolators within the cycle of the reference clock, and the phase differences between the input hit signal and the reference clock are kept in the SROs for further interpolation with time domain successive approximation. Thus, the SROs operate as time domain sample and hold circuits. The SROs are active only when the time interval digitization takes place to save power.

The layout design of the TDC was finalized during 2015 and the design database was sent to the foundry in November 2015. The prototype circuits are expected in the first quarter of 2016. The measurement system is currently under development. The nominal resolution of the TDC is ~1.6 ps with 15 stage SROs and effectively 8-bit successive approximation. The dynamic range of the TDC is ~0.2 ms with a 15-bit counter.

Optical Receiver Circuits

An Integrated CMOS Receiver Channel with a TDC for the Pulsed Time-of-Flight Laser Ranging

An integrated receiver channel has been developed in 0.35 μm CMOS technology for a pulsed time-of-flight (TOF) laser radar. The main function of the receiver channel of the pulsed TOF rangefinder is to generate an accurate logic-level timing signal to a TDC. As the accuracy of better than 1 cm was aimed at, a specific timing point must be discriminated from the detected laser pulse (FWHM ~ 3 ns corresponds to about 50 cm in distance). Simple leading edge detection would suffer from low measurement accuracy in the applications where the dynamics of the received echo varies a lot (> 1: 10 000). The new receiver channel architecture enables to detect two timing parameters, the pulse width and the slew rate of the detected pulse echo. These are measured with a multi-channel TDC and used for the walk error compensation. The receiver channel consists of a transimpedance pre-amplifier, voltage type post-amplifier, a threshold generator for the timing detection and two parallel comparators generating logic-level timing signals for the TDC.

The measured transimpedance and 3 dB frequency are ~100 kΩ and of ~230 MHz, respectively. The walk measurements were performed by sweeping the amplitude of the input optical pulse over a range of ~ 1: 200 000 with a neutral density filter. First, look-up tables (LUT) were measured for the calibration of the receiver channel. These tables contained compensation information on the relation of the timing walk error to pulse width within the signal range of ~ 1: 200 000 and the relation of the timing walk error to the slew-rate within signal range of ~ 100: 200 000. The measured walk error without compensation, as shown in Figure 8, was about 2.5 ns (correspond to 40 cm in distance).

Figure 8. Measured uncompensated walk error.

The measured and compensated residual walk errors are shown in Figure 9. The residual walk error is about ±15 ps (±2.3 mm) within a dynamic range of 1: 200 000.

Figure 9. Compensated, residual walk error.

The single-shot precision of the receiver channel is determined by the noise of the timing point at the detection threshold and the precision of the TDC. 10 000 single shot measurements were performed at a specific input amplitude and standard deviation of the timing point of rising edge were calculated. In another meas-
urement, each of the individual measured result was corrected by means of compensation curve (walk vs width) and the single-shot precision was calculated from the achieved distribution. The worst case single-shot precision of the whole receiver was about 170 ps at the minimum usable signal level as shown in Figure 10.

![Figure 10. Single shot precision.](image)

The die of the receiver channel is shown in Figure 11. The size of the receiver die is approximately 2 mm × 2 mm and it is packed in a QFN36 package. The total power consumption is about 185 mW from a 3.3-V power supply.

![Figure 11. Die of the receiver channel.](image)

The final goal is to integrate a high-performance receiver channel and a multi-channel TDC (time to digital converter) on the same IC chip. A miniature receiver channel/TDC chip will be realized to serve numerous applications in the field of pulsed of time-of-flight laser radars.

**Pulsed Time-of-Flight Systems**

**Laser Diode Transmitter for Single Photon Detection Based Ranging**

A compact laser transmitter with a CMOS driver (0.35 μm HV-CMOS technology) has been developed and tested in pulsed time of flight laser ranging finding utilizing single photon avalanche diode detection (SPAD). The measurement setup is shown in Figure 12. The driver can be triggered with 1 MHz pulsing rate at a peak optical power of ~3 W / 100 ps.

![Figure 12. Compact laser diode transmitter and the measurement setup.](image)

The laser transmitter uses a 30 μm / 1.5 mm QW laser diode. The energy and the width of the optical pulse were measured to be ~0.3 nJ and ~100 ps, respectively with a current pulse of ~2 A and pulse width of ~1 ns. The peak optical power as a function of the peak current of the driver is shown in Figure 13.

![Figure 13. Optical peak power as a function of the peak current.](image)

To demonstrate the resolution of the measurement setup, a single-shot precision measurement was carried out with a target that had a step within the illuminated area having the overall reflectivity of 8%. Step sizes of 2 cm and 3 cm were used in this measurement, and 100 000 pulses were transmitted to a target at a pulsing rate of 100 kHz. The hit distributions are shown in Figure 14. All measurements were carried out in a standard laboratory environment with a background illumination level of ~100 lux.

![Figure 14. Hit distributions of measurements in which the target has step sizes of 2 cm and 3 cm within the illuminated area.](image)
Pulsed TOF Laser Rangefinder with a 2D SPAD-TDC Receiver

A pulsed time-of-flight laser radar based on a high speed/energy optical transmitter and a SPAD-TDC receiver has been developed. The transmitter employs a bulk double heterostructure laser diode operating in enhanced gain switching mode at a wavelength of ~870 nm, giving ~1 nJ / 125 ps optical pulses. The receiver is a single CMOS chip consisting of a 9x9 CMOS SPAD array and a 10-channel 10 ps precision TDC. The 2D detector array releases the required precision and tolerances of the opto-mechanics of the radar. Any of the 3x3 sub-arrays within the 9x9 array can be selected for simultaneous measurement, and the selection can be altered flexibly during measurements, e.g. to follow movements of the target image at the detector surface. Adjustable-width time-gating windows of down to ~5 ns can be used to suppress background hits. A single shot precision of ~170 ps (FWHM) and a measurement range of tens of metres with non-cooperative targets have been achieved with an 18 mm receiver aperture.

Figures 15 and 16 show the block diagram and the implementation of the laser rangefinder.

The measured detection probability from a diffuse target at the distance of ~24 m and with a reflectance of 3% was ~60% (~1 detection for 2 laser shots). Figure 17 shows measurement results of single shot distributions for three targets with three different reflectivities (i.e. three received light intensities) located at the distance of ~24 m: single photon detection mode (green), ~3x10^5 times higher received light intensity (black) and ~10^7 times higher received light intensity (red).

The results show promise for the construction of very compact pulsed time-of-flight laser radars and imagers (2D, 3D) with high performance in terms of precision and measurement range.

Multiphase Time-Gated Single Photon Avalanche Diode (SPAD) Arrays for Raman Spectroscopy

Raman spectroscopy is based on inelastic scattering of monochromatic light, usually from a CW (continuous wave) laser in the visible, near infrared or near ultraviolet range. Typically, the Raman spectrum is masked by a strong fluorescence background. This strong fluorescence background has so far restricted the use of Raman spectroscopy in many potential applications.

It is possible to suppress the fluorescence background markedly if intensive short laser pulses are used to illuminate the sample in such a way that the sample response is recorded only during these short pulses. The suppression is due to the fact that Raman scattering is introduced immediately after the collision between the photons and the sample material, unlike fluorescence, which is emitted after a delay characteristic to the sample. Thus, by “time-gating” the measurement for only the period of the laser pulse, most of the fluorescence is blocked out from the recorded spectrum as shown in Figure 18.

At the beginning of this decade we presented the idea of using a time-gated single photon avalanche diode (SPAD) detector in a Raman spectrometer to suppress the high fluorescence background. Several versions of the time-gated SPAD arrays have been developed during the past five years. Our latest time-gated SPAD array consists of 16*256 pixels and a 3-bit 256 channel
TDC. It has been characterized in a specially developed test environment. Any single pixel can be stimulated with a short laser pulse in the single photon mode and the timing skew of the 3-bit 256 channel TDC can be measured.

Figure 19 shows the timing skew of the SPAD array as a function of the spectral point (2*128). The maximum error is ±75 ps. In addition, the timing skews of every timing signal of the 3-bit TDC were measured and the widths of the bins and their deviations are shown in Figure 20.

As an example, Figure 22a shows the Raman spectrum of a “difficult” sample, sesame seed oil, which has very high fluorescence background and short life time (2 ns), measured with the above system. The Raman peaks can be clearly visible contrary to what is seen in the Raman spectrum measured by using the traditional technology, a CW laser and a CCD, as shown in Figure 22b.

In addition to the circuit design, a time-gated Raman spectrometer based on a pulsed laser, a spectrometer, a single movable SPAD detector and a time interval measurement unit has been constructed. The block diagram of the developed measurement system is shown in Figure 21. A single SPAD detector with a micro step motor is used to overcome the performance limit of a SPAD array detector. Every spectral point is measured by using the same detector and time interval measurement unit resulting in a clean spectrum from the point of view of any detector and time gating mismatches.
High-Power Pulsed Emitters for Sub-THz Imaging and Physical Principles of Avalanching BJT’s Operation in Ultra-High-Voltage/High-Speed Generators.

Si avalanche BJT’s have been most frequently used for nanosecond pumping of pulsed laser diodes, but operation principle of Si avalanche transistors at extreme current densities and with a switching time around 2-3 ns was absent until the last decade. First reliable 1-D and 2-D description of the process we made a decade ago, while within last few years we have experimentally proved that the parameters of short-pulsing avalanche switching cannot be explained (or predicted) without consideration of fairly complicated 3-D transient phenomena. Recently, we have mainly finalized the problem in general by description of 3-D transient peculiarities during both delay and fast switching phases.

Next, the challenging task consists in physical understanding of avalanche transistor operation in kilovolt- and picosecond pulse generators utilizing direct serial connection or Marx-bank circuit shown in Figure 23. Every year within last five decades appear several publication presenting new generators utilizing this principle, they are used in very large number of fascinating applications, but until nowadays an operating principle of a single transistor in the chain, which has emitter-base electrodes externally short-connected has been unknown. Very recently we have shown that bipolar avalanche transistor switching with base-emitter shunted consists of two stages. The first, initiated by high (~2.5 kV/ins) voltage ramp, is caused by diode-like double avalanche injection of the electrons and holes into the n<sub>0</sub> collector, and can provide as fast as ~20 ps voltage reduction down to ~30 V, but only as a transient (non-steady-state) voltage reduction, see Figure 24. This switching then provides the necessary conditions for the second stage, at which transistor-like quasi-steady-state turn-on with low residual voltage is realized thanks to electron injection from the emitter. Since electron injection at short-connected base and emitter is impossible in 1-D case, understanding of the phenomenon required 2-D approach to be implemented. Low residual voltage is important for effective operation of Marx generator in the nanosecond range, while the first switching stage is of practical significance for picosecond pulse generation. These results created for the first time basis for the physical understanding of the operation of Marx-bank generator. Particularly interesting is the fact that entire emitter area operates in Marx-bank regime, unlike only emitter-base perimeter in ordinary switching mode.
This research is in the very beginning, and in practical meaning it promises (i) very important understanding to be achieved in optimal circuitry and optimal transistor chip selection for high-speed, high-voltage generators; (ii) physical interpretation of picosecond high-voltage switching, which problem remains still an open question; (iii) development of unique microwave emitters is sub-cm wavelength range generating high-power picosecond pulses using commercial BJTs.

Much more impressive than avalanche switching in a Si BJT is that in specially designed and manufactured GaAs bipolar structures. Together with high-current/short pulse generation, a very promising (and apparently most important) application for the avalanche switching in GaAs BJT is the generation of pulsed broad-band sub-terahertz emission.

Periodical nucleation and annihilation of ultra-narrow, powerfully ionizing “collapsing” domains is shown to cause sub-THz emission observed in our experiments. The task of design, development and investigation of high-power pulsed (ns/sub-ns) emitters for a new generation of active sub-THz imagers should be divided into several directions and stages, and this is the major part of our strategic TEKES project (MIWIM) started in 2014. Principal direction is the design and development of BJT GaAs-based structures combined with properly designed sub-THz antennas. The solution of a number of complicated physical, technological and mm-wave propagation tasks is underway, and the first laboratory examples of transmission sub-THz imaging utilizing not only transmission intensity, but also propagation delay of the pulses across the object have been reported in several plenary and invited talks. The results from our first prototypes of millimeter-wave radars are at a very early stage however.

First examples of transmission images obtained in both attenuation and propagation delay modes, obtained using a prototype of our completely original sub-THz emitter in combination with commercial Schottky detectors are shown in Figures 25 and 26. Work on significant improvement spatial and temporal resolution of our prototypes of mm-wave radars and imagers operating both in propagation and reflection modes are going on successfully.

The phenomenon of collapsing field domains is under extensive theoretical, numerical and experimental investigation. It has been particularly shown that the phenomenon fundamentally allows the emission to be generated up to 1 THz.

Demonstration of successful examples in which our emitter shows its very high application potential is the priority direction of our activity, especially as soon as it concerns prompt commercialization. Some interesting application examples have already been found, tested, shown to representatives of companies, and positive evaluation of commercial prospects have been received from them.

Figure 25. Two photos, X-ray transmission image, and two sub-THz transmission images of a tap. The upper sub-THz image, together with attenuation of the radiation in thicker parts of the tap, displays attenuation (red ring) near the edge of the object. This is caused by the diffraction and creates an erroneous idea on the tap shape if it is hidden in a box, or is a hidden part of a more complicated object. The lower image utilizing the propagation delay is free of this defect of the attenuation imaging. The total delay range between blue and red levels is about 25 ps.

Figure 26. Plastic explosives have chemical composition and THz absorption spectra somewhat similar to sugar and soap. In the photo (up/left) there is a cell from the organic glass filled with granulated sugar in which several pieces of lump sugar and one bar of soap are hidden. X-ray image (up/right) hardly recognizes the lump sugar, and does not show the soap at all. In the attenuation sub-THz imaging the boundaries are well resolved thanks to the diffraction, but the most correct impression on the object is provided by the propagation delay image (the lowest). Moreover, in very homogeneously looking soap bar the propagation delay image shows certain structure with the delay difference (yellow/dark red) of about 10 ps.
5G RF IC design

Prof. Aarno Pärsinen from CWC has started several projects related to IC design for future 5G systems, and asked Prof. Rahkonen and Dr. Aikio from CAS group to join the effort. The effort started by recruiting and training three new PhD students, that will be jointly supervised by Profs. Pärsinen and Rahkonen. During autumn 2015 two high-speed MOS silicon-on-insulator processes were evaluated, and eventually PD-SOI process was chosen. During late autumn, the design of a beam-steering 15 GHz transceiver IC with with 500 MHz bandwidth and a total of eight transceiver pairs was started, and the expected tape-out is in March 2016. Dr. Aikio designed a stacked power amplifier for the transmitter, Dr. Kursu the digital trimming and control logic with ca. 700 control bits, and Rahkonen proposed the digitally controllable phase shifter architecture.

The main interest in this research is to find efficient integrated implementations for multi-antenna transceivers. One especially challenging topic is how to arrange the linearization and efficiency improvement of the power amplifiers, as contrary to modern systems, there are a multitude of separate power amplifiers with different power levels, and also the aimed bandwidth is much larger than in current transmitters. Some preliminary research on this topic has been conducted.

Biomedical Applications

Aimed for measuring nerve signals in small insects, a 16-channel nerve signal measurement IC was designed for a 0.35 µm CMOS process during 2014. A test setup consisting of Atmel CPU serving as a 3.5 Mbps SPI to USB bridge was built, and the IC was functionally tested during 2014/2015. The measured noise performance was as expected. The DNL of the multiplexed 10-bit SAR was good enough, but due to a signal-dependent gain of the rail-to-rail dynamic comparator the INL error increased toward the other rail. After electrical tests, also the nerve signals of a cockroach’s leg were measured to verify that the circuit works with a real source impedance, too.

The results were published in Springer journal of Analog integrated circuits and signal processing during spring 2015 (see selected publications), and Olli Kursu defended his PhD thesis in December 2015.

Electronics for photovoltaics

PhD student Christian Schuss has been studying – together with researchers in NEGOMA group - the use of thermal imaging in detecting wiring faults and cracks in photovoltaic panels. The technique does not require precise white illumination and cooling for standardized test conditions, but instead relies on the self-heating of an externally biased photovoltaic panel. The results were reported in I2MTC conference, was extended to journal paper in Trans on Inst. and Meas. during autumn 2015.

Design of delta-sigma ADCs

The loop response of delta-sigma analog-to-digital converters is most often designed using Richard Schreir’s classical Delta Sigma Matlab toolbox. Dr. Marko Neitola improved the goal definition for the numerical optimization of the noise-shaping transfer function (NTF), and the improvement has been included in the Delta Sigma toolbox. During the autumn he also improved the rule-of-thumb norms that set the starting point for a practical NTF, and the findings were submitted to IEEE TCAS journal.

Doctoral Theses
