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THz imaging for recycling of black plastics

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Abstract This paper presents the development of a novel line-camera device in the THz-domain which is capable of measuring minute differences in broadband spectral fingerprints of non-conducting materials. The primary focus is sorting black plastics in industrial recycling contexts, where large scale sorting of different types of black plastics remains a challenge. The system operates from 84 GHz to 96 GHz. As the relevant plastics exhibit no specific absorption lines in this frequency range, a broadband approach is necessary to accumulate slight differences in dielectric properties into enough entropy that a machine learning algorithm can be trained to differentiate between different materials even in the presence of contaminants such as flame retardants, color pigments and dirt. Preliminary results suggest that the blackValue® THz sensor system is capable of achieving these goals.

Keywords: THz imaging, black plastics.

1 Introduction

The thermal recycling of plastics is no longer seasonable for modern industrialized countries; in 2011 unfortunately around 56 % of all plastic scrap in Germany was recycled thermally. These 3 million tons of plastic scrap are an untapped treasure for a resource deficit country. Non perfect sorting results in low-grade plastics granulate which in turn can only be used to produce lower grade products. Today recycled material is mixed together with new raw material to create a high-grade granulate. The drawback of this procedure is, that for 1 t recycled material between 2 t and 3 t new material is needed. For a 100 % material recycling strategy a mono-fraction sorting system is the key to success.

Modern recycling systems use hyperspectral camera systems to distinguish between different plastics. Because of the high carbon content in black plastics most of the photons of optical detector systems are absorbed. For efficient sorting systems new sensor concept are needed.

Test measurements and publications in the last few years have shown the feasibility of plastics separation using THz systems. While plastics can be identified using their distinct absorption lines in the infrared region, in the lower THz region they exhibit no such behavior [1]. To choose the optimum frequency range, a selection of machine learning algorithms was trained with test data sets acquired in the first phase of the project. Test series with commercial systems show that better sorting results can be realized using higher frequency ranges as well as more bandwidth for the analysis. With a limited number of classes, test sets and a first prototype algorithm a probability between 85 % and 95 % for identification was realized [2]. The chosen frequency range is a compromise between the need to design an economically priced commercial system while simultaneously achieving a high purity level.

2 Measurement principle

The blackValue® THz line scan camera system utilizes a stepped-frequency continuous-wave (SFCW) approach. The transmitter illuminates the particles traveling on the conveyor belt with 128 equally spaced frequency lines in the lower THz region ranging from 84 GHz to 96 GHz, yielding a usable bandwidth of 12 GHz. The receiver uses a quadrature mixer to downconvert the received signal to an intermediate frequency (IF) of 3 MHz. This IF signal is sampled using a 25 MSps analog to digital converter (ADC). Only a single sample is captured per frequency step as the information contained in the quadrature signal (I, Q) allows for the reconstruction of instantaneous magnitude $\mathrm{A}(t)$ and phase $\Phi(t)$ of the received signal: $\mathrm{A}(t) = \sqrt{\mathrm{I}(t)^2 + \mathrm{Q}(t)^2}, \Phi(t) = \arctan \mathrm{I}(t)/\mathrm{Q}(t)$. The sample instant has to be timed precisely as a sample captured early or late exhibits artifacts stemming from the system still settling on the current frequency or the most recent frequency step, respectively.

While this approach requires careful timing, it enables us to decrease the acquisition time for a complete measurement frame (128 frequency steps, arbitrary number of sets of 4 channels multiplexed in time) to less that 1.4 ms.

Unless filtered in the analog domain, each sample contains the noise integrated over the whole analog bandwidth of the ADC, thus raising the overall noise floor and decreasing system signal-to-noise ratio (SNR). This effectively puts a lower bound on the IF frequency as lower frequency filters require larger components, making designs below 1 MHz impractical. At higher IF frequencies, sampling jitter leads to inaccuracies in the captured phase of the IF signal.

As the system is intended for recycling applications, a large bandwidth of additives, material mixes and impurities is to be expected in the measured goods. A simple fingerprint analysis comparable to absorption line evaluation is not sufficient to achieve satisfactory sorting results in the used frequency domain. Therefore, a machine learning algorithm is trained to perform the actual classification based on the captured and normalized magnitude and phase information. The principle was demonstrated in [3], while [2] performed measurements using the precursor of our current system.

3 Hardware concept

Typical conveyor belt speeds for this application are in the range of 2.5 to 3 m/s. As the system should be able to provide a resolution of around 1 line per millimeter a measurement-rate of up to 3000 measurements per second has to be achieved. This yields in a interval of less than 333 μs available for the generation of all frequency-lines in the desired range and the synchronous sampling of the down-converted RX-signal, which contains the permittivity-characteristics of the probe. In the following subsections the frontend and the backend of the system will be described in more detail.

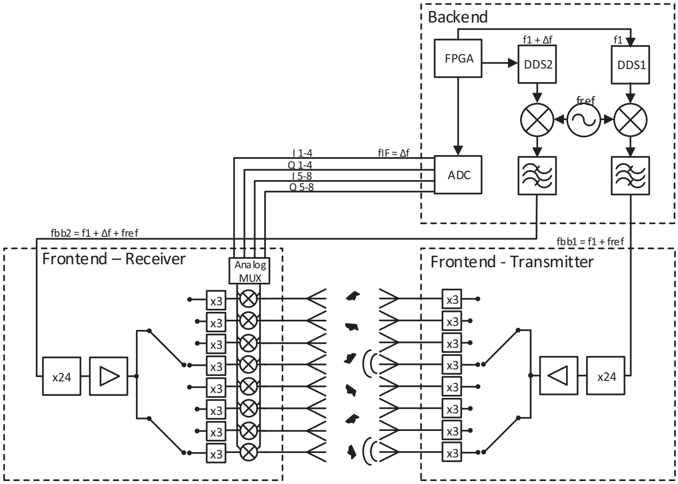

Figure 21.1: Schematic illustration of blackValue® THz Imager.

3.1 Frontend

The frontend consists of an array of transmitters and receivers which can be cascaded in a modular fashion to allow for the required number of channel (or pixels). This is evident of the desired covering width of conveyor belt and the resulting resolution of the THz camera-system. The measurement method is similar to a simplified multi-port heterodyne vector network analyser. The fundamental idea of the blackValue® system is illustrated in figure 21.1.

Two Direct Digital Synthesis (DDS) chips generate fast stepped frequency ramps f_1 from 160 MHz up to 320 MHz in which the ramps are slightly shifted in frequency Δf with respect to each other. Both ramps are upmixed using the same low noise reference oscillator f_{ref} and the resulting conversion product is bandpass filtered. This baseband signals f_{bb} with frequency range from 1,16 to 1,33 GHz feeds into the transmitters and receivers. Using a chain of multipliers the baseband signal gets upconverted further to an RF signal band ranging

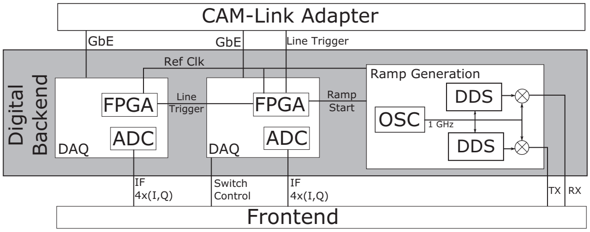

Figure 21.2: Schematic overview of the digital backend of the blackValue® sensor.

from 27,8 to 31,9 GHz. This signal then feeds an RF switch. The switch is controlled by the backend and allows to switch the transmitting antennas in Time Division Multiplex (TDM). this way, a trade-off between optimal performance and economical costs can be achieved.

The spatial separation between active antennas allows for insignificant crosstalk and multiple usage of the 30 GHz LO reduces the system costs. After passing the switch the RF signal gets multiplied again to the targeted millimetre-wave band ranging from 83, 5 GHz to 95, 8 GHz and is radiated by the transmitter antennas. After passing a plastic flake the affected millimetre-wave signal gets detected by the receiver antennas. The receiver involves an IQ-mixer, which converts the affected signal together with the slightly shifted LO signal down to an Intermediate Frequency (IF) of 3 MHz. Depending on the currently active pixel, the corresponding IF signal is switched by an analog multiplexer to the backend.

3.2 Backend

The digital backend of the presented THz camera system consists of multiple distinct subsystems as depicted in figure 21.2 and described in the following paragraph.

A ramp generator board serves as source for local oscillator signals for the receive- and transmit-path as well as source of a digital reference clock signal for synchronous operation with the data acquisition (DAQ) boards. These Signals are generated by a 1 GHz reference-oscillator that drives a clockmanager IC which in turn drives two DDS-ICs.

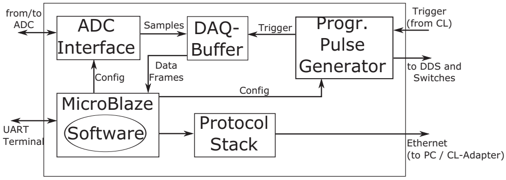

Figure 21.3: Block-diagram of the DAQ-FPGA firmware. Timing- and performance-critical tasks are implemented in hardware-modules which are controlled by software running on an embedded microcontroller.

Coherent sampling of the downconverted RX Signal is accomplished by a set of 8-channel DAQ boards. As for every pixel a complex quadrature IF signal is captured, each of these boards allows simultaneous sampling of 4 Pixels. By time-division multiplexing of 4 IF channels from the frontend, each DAQ board is capable of capturing 16 pixels of the scanline. Multiple DAQ boards can be combined to acquire scanlines containing more than 16 pixels, where one of these boards acts as a master device, controlling the signal-generator board and distributing a synchronous line-trigger signal to all slave DAQ boards as well as controlling the signal mutiplexers.

Figure 21.3 gives a schematic overview of the firmware-logic realized in FPGA-hardware on the DAQ boards. The control signals for sequencing the operation of the signal-generator, the RX/TX switches and the sample-buffer are generated by a programmable pulse generator, which is implemented in FPGA logic-ressources.

Different schedules for these control signals may be loaded to this pulse generator by software running on an embedded microcontroller (MicroBlaze^{TM}). Figure 21.4 illustrates the pattern of pixel-multiplexing and frequency switching as employed in the current version of the sensor. Each DAQ-device transfers its acquired stream of 16 pixels over a Gigabit-Ethernet link via UDP/IP-Packets. A seperate FPGA-based Camera-Link adapter-board bundles these streams for subsequent transmission via camera-link.

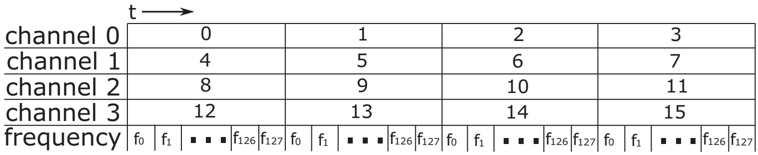

Figure 21.4: 16 complex-valued pixels are multiplexed to 4 complex channels on the DAQ board.

As the imaging system is intended for industrial applications, serviceability and scalability are a primary concern. While earlier approaches [4, 5] depended on custom-machined housings comprising delicate waveguide structures, these expensive one-off parts are superseded in our current build-up by using commercially available launch connectors and individual printed circuit boards (PCBs) for each channel.

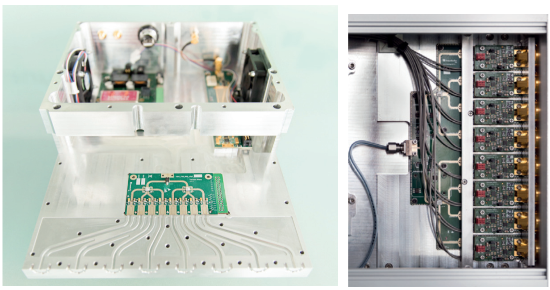

Figure 21.5: Left: Old frontend with machined waveguides. Right: New frontend using single channel PCBs and plug-in wave guide launch adaptors.

Earlier backends were tightly integrated with PCBs stacked in multiple layers. Although layers were functionally independent where possible, 30 GHz gain blocks and reference signal generation had to be placed on the bottom of the casing to facilitate thermal management. While this setup was used to successfully demonstrate the feasibility of our approach [2], it imposed limits on scalability with respect to the number of channels used.

To overcome these limitations, a more modular approach is neccessary. Our current system concept is centered around using a motherboard to distribute power and route all critical RF signals to a multitude of daughterboards. We opt for using PCIExpress-connectors as these provide well defined insertion and return loss specifications over a wide frequency range while as a consumer grade product being readily available at a low price. A basic set of daughtercards is used in the current system: The first one conditions the RF reference signal and controls the RF TDM switches in both the receive and the transmit frontend modules. A second daughtercard implements a 4 channel high pass filter bank for the measurement signals being captured from a single frontend module. This card is also used to control the RX TDM switches in the frontends.

System partitioning is driven by the need to perform a transmissive measurement, meaning the transmitter is situated on top of the conveyor opposing the receiver below. On an industrial scale conveyor, this necessitates cable trunks spanning multiple meters between the backend and the frontend. This limits the frequency distributed by the backend to the low GHz range.

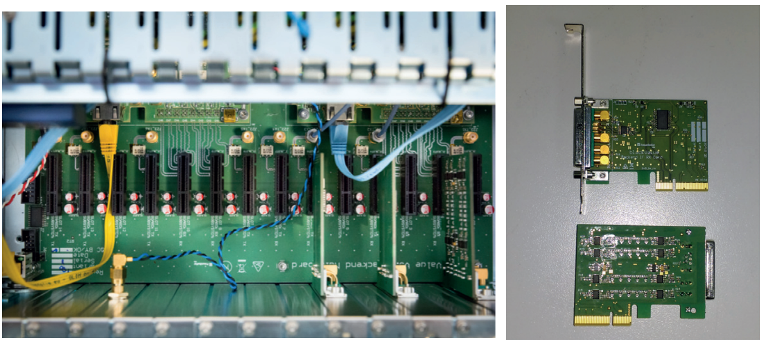

Figure 21.6: New modular backend in COTS case with plug-in cards.

Figure 21.7: Spectral fingerprints of different materials. Channels are oriented vertically while frequency increases from left to right. Top right: No specimen. Bottom right: Aluminium sheet, resulting in noise. Top left: 1 mm ABS sheet. Bottom left: 1 mm PP sheet. Areas containing distinguishing features are highlighted. Signals are intentionally overdriven to enhance visibility of features.

4 Results

To evaluate system performance, pure polymer samples are measured using the blackValue® camera. As the classification algorithm builds on a large database of scanned materials, a different approach is used to assure enough measurement entropy before conducting large scale training data acquisition. Plastic sheets measuring $150\,\text{mm} * 150\,\text{mm}$ with a thickness of 1 mm are placed into the measurement aperture and the resulting spectral fingerprint is recorded. Normalization is performed using a reference measurement without a test specimen. The resulting spectral fingerprints are visualized in Fig. 21.7. Although the differences are quite small, they allow classification of the pure specimen.

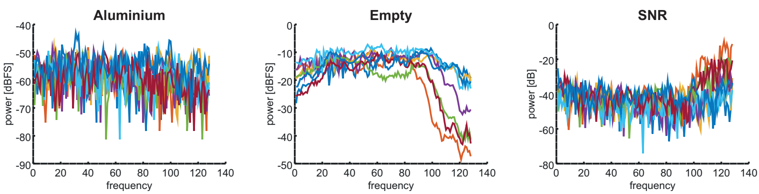

Figure 21.8: Signal-to-noise measurements. The first graph shows the system noise floor for each frequency line and channel. The second graph shows the reference measurement. The last graph shows the calculated system SNR.

The noise level of the receiver is measured using a 3 mm metal sheet isolating the transmitter and receiver. This is compared against the measurement without a test specimen. The difference of these measurements (in dB) defines the frequency and channel resolved system SNR. Fig. 21.8 shows the result of this evaluation. For frequencies up to 93.375 GHz (step 100), system SNR reaches $35 - 40$ dB. As the frequency increases further, some channels show degraded performance. This is to be expected as the 30 GHz switches used in the frontend exhibit insertion loss imbalances across channels at higher frequencies.

5 Future work

The final blackValue® system comprises the THz line scan camera as well as classification algorithms and a sorter that performs particle flow segmentation using an optical line scan camera. The next steps are integration of the THz sensor into the TableSort bench sorter developed by Fraunhofer IOSB and teaching the classifier developed by Fraunhofer IAIS using a wide range of real world particles, i.e., particles originating from recycling processes. Following successful integration, the sensor array will be extended to 32 complex channels (pixels) and integrated into the FlexSort large scale sorter. Additionally, we are working on implementing steeper and narrower IF filters which should further increase the system SNR.

6 Summary

A W-band THz line scan sensor array comprising 8 channels with a bandwidth of 12 GHz was realized. We demonstrated the fitness of the blackValue® THz sensor for the task of sorting black plastics by evaluating its RF performance and noise level.

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