T-Sense - the New Generation of Non-contact Transmission Imaging with Non-ionizing Radiation

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Abstract. The detection of impurities, air gaps and material fluctuations inside of packed products is an increasing challenge for modern production processes. To detect defects like metallic particles, metal detectors and x-ray systems are common and part of security and quality concepts for manufacturing. Until now, x-ray and ultrasound imaging systems are the only chance to view inside a product and to detect enclosed impurities which are not visible from the surface. Unfortunately ultrasonic systems need a medium, such as water between the measurement head and the device, to feed the ultrasonic signal into the product. On the other hand X-ray systems offer the possibility of non-contact inspection and high resolution. The main disadvantage of this technology is the ionizing radiation. Millimetre wave inspection systems offer the possibility of realizing a non-contact transmission image of materials like x-ray systems do, with the advantage of non-ionizing radiation. Through the phase, amplitude measurement mmw-wave imaging systems offer a high sensitivity which allows the detection of small variations inside a product. Due to the increasing number of applications in the course of last years, the components for this technology become cheaper and cheaper. Through the cooperation of FHR and Hübner, a fast table scanner was realized as a commercial product for the first time. The simple and fast scanning system consists of two rotary discs and a conveyor band. One antenna is mounted on the transmitter disc and the other one resides on the receiver disk. During the rotating and scanning process, both antennas face each other. The Device Under Test (DUT) moves on a conveyor band linearly between the two antennas. Both rotary discs are mounted inside a chassis, driven by one actuator to ensure the same rotary velocity and angle of both discs. The quick look and further signal processing will be done on a fully integrated computer which is controlled by user interaction. The system works fully coherent and it is possible to analyse not only the attenuation, but also the phase values shifted by the dielectric properties of the product. The measurement configuration of T-SENSE® is a common transmission alignment. To decrease the cost of such a scanner system, the transmitter and the receiver are based upon commercial millimetre wave components.

Keywords T-SENSE, mm-wave scanner, food inspection, security scanner

1. Introduction

Today, many applications like security controls, medical applications or the development of new products would benefit from fast and cheap imaging systems. New sensor concepts
that are working in the millimeter wave range offer an alternative to optical or X-Ray systems [1]. On the one hand, examinations with X-Ray methods are common but cause high costs due to the necessary safety regulations. On the other hand, optical sensor systems are cheap, but offer only limited information about the internal structure of the DUT. The usage of millimeter and sub-millimeter waves is a promising alternative to the classic approaches. The frequency range of interest covers the region between the classic radar and communication bands (below 40 GHz) and the infrared band (above 1 THz).

Higher frequency ranges in the THz region are possible and interesting for spectroscopy analysis but for imaging systems to slow and expensive at the moment. Systems in this frequency range offer better transmission measurement capabilities than the IR or optical frequency range and achieve better resolution compared to classic radar bands due to the optimal wavelength. To develop a cheap millimeter wave imaging system, it is necessary to minimize the number of active high frequency channels. The smallest number that is possible, is a single channel sensor in combination with a 2D mechanical scanner concept. The reduction of channels is possible through the fast measurement speed of high frequency systems. High frequency systems typically use no detector concepts, which allow update rates between several thousand and hundred thousand measurements per second. Most scanning approaches are based on a motorized XY-scanner, which moves the high frequency sensor in a reflection or transmission configuration around the DUT. In combination with a focusing antenna, a lens system or a near field probe, these system concepts produce high resolution millimeter wave images. The main disadvantage of 2D scanner systems is the poor scanning speed. An imaging system with a high precision stepper motor needs over one hour for an image of a chocolate bar (Fig. 1) with a typical size of 7.5 cm x 15cm.

![Fig. 1. Measured chocolate bars (7.5x15cm each) one with and one without impurities.](image)

The measurement was done at 260 GHz.

Faster motor concepts with a lower positioning accuracy can realize such a measurement in one or two minutes. But even with this improvement in speed, mechanical XY-scanner concepts are far away from the measurement time that is needed for inline quality control systems in production lines. The analysis of these motor concepts shows that the time loss result mainly from the de- and accelerating of the linear motor stages. The change of direction causes a dead time, which slows down the entire measurement system. A promising approach for speeding up the measurement is switching from a linear motor concept to a rotating scanner approach.
MECHANICAL SCANNING CONCEPT

The presented scanning system is based on a bistatic antenna concept. The antennas are mounted on two rotating discs or arms, facing each other. It is important that both antennas are driven by a single actuator or a synchronized direct drive concept, to ensure a synchronous movement of both antennas. The sample moves linearly on a conveyor band between the two antennas. The distance between the antenna structures is 4 centimetres. Therefore, the maximum height of the DUT should not exceed 3 cm.

Both rotary discs are mounted inside a chassis, driven by one actuator to ensure the same rotary velocity of both discs. Based on the motor concept and the maximum rotating speed of the rotary joint the maximum angular speed is limited to 8 Hz and the maximum form feed to 3m/min.

III. SCANNER CONCEPT

The transmitter and the receiver paths are based upon commercial millimeter wave components. The system works fully coherently and thus it is possible to analyse the phase values shifted by the dielectric properties of the sample in addition to the attenuation caused by the DUT. The centre frequency of the system is below 100 GHz because it represents a good compromise between achievable resolution and the resulting material costs for the high-frequency components at the current time. In the last couple of years this frequency range was pushed through SiGe chips for the anti-collision radar systems (e.g. [2]).

The system concept is based on a continuous wave (CW) signal. System concepts with a frequency modulated continuous wave (FMCW) are possible but challenging because the frequency ramp generation has to be very fast. The second generation of the scanner will use a frequency band around 94 GHz with a bandwidth of 8 GHz. At the moment only CW systems are commercially available. It is impossible to achieve a range resolution by using a CW signal. The system can be roughly divided into three modules. There is a rotating transmitter module (TX), a rotating receiver module (RX) and in each case a stationary part for frequency generation and the processing of the received signals. Vital for this rotating concept are the rotary joints (RJ), which provide the ability to transfer high frequency (HF) signals and a DC power supply at the same time. The usage of this RJ eliminates the need of an additional slip ring to transfer the DC power. The RJ cannot transfer the measurement frequency directly. Therefore an active triple stage TX module is used to multiply and amplify the frequency up to 78 GHz. The first stage is a frequency doubler, followed by a
frequency tripler in a second stage. The maximum output power after the last amplifier (third stage) is 10 dBm. Multiplying the TX frequency on the rotation platform has the advantage of being able to quickly adapt the measurement setup for different applications without changing the basic generation or the IF processing. The basic frequency is generated in the stationary RF module and fed in the transmitter and the receiver to create a coherent measurement setup. The two Bias-T’s (one in the stationary and one in the rotating section) are used to combine and separate the DC power from the HF signals.

In the receiver path the same rotary joints and Bias-T’s are used to transfer the power and the RF signal. Since the RJ is not able to transfer the measurement frequency, the received signal is converted down using a mixer. The stationary generated frequency is used as LO and fed into the RX-Module. The RJ offers only one RF channel. In order to transmit the LO onto the receiver and the IF signal down to the stationary processing, two diplexers (DPX) are used to combine and split the frequencies. In the stationary RF processing an IQ-Mixer is used for down converting the received signal. Subsequently, the I- and Q-signals are fed to the ADC. The digital backend consists of two analogue digital converters (ADC), which are controlled and read out simultaneously by a digital logic built up on a field programmable gate array (FPGA). As mentioned above, the analogue signals are produced by a rotating system.

The arc, which is traversed by the antenna configuration eight times a second, has a diameter of 300 mm, corresponding to a circumference of 942 mm. To achieve an image resolution in range of one millimeter or less, the data acquisition has to record at least 1000 points of measurement per round. Since for each pixel amplitude and phase value have to be recorded, the number of data points sums to 2000 measurements per round (minimum requirement). With an ADC quantization of 14 bit there would be a resulting data stream of 224 kBit/sec. The actually used sampling rate is 5 MSp/sec resulting in a pixel data stream of 140 Mbit/sec, which has to be processed during measurement. The used sample rate exceeds the minimum requirements, delivering some more data to allow averaging and advanced processing. The built-in control logic assures that both channels (I/Q) are sampled synchronously, which is vital for the amplitude and phase calculation later on. For the proof of concept the further data processing (like transforming the measured arcs of pixels into a rectangular image) has been implemented on a computer. The communication between FPGA and computer is based on an Ethernet network link.

One of the next steps in development will be not only to improve the image quality by increasing the sample rate, but also to speed up the data processing by relocating algorithmic functions of data processing to an FPGA or system on chip (SOC). The antenna system was realized with a dielectric tip. For the tip polyethylene (PE) with a relative permeability of 2.25 was used.

IV MEASUREMENT RESULTS

Measurements done with the T-SENSE imaging system are to be evaluated by eye and therefore judged by human personnel. The software offers different colour code options, but all of them work in a relative way. No matter of how big the dynamic range of the detected signal difference is, the software projects the full colour code or grey scale onto this difference. Even though one will not get absolute values, this method has itself proven to be more soothing to the human eye and the person evaluating the images has a lesser probability of missing even small changes in the colouring indicating a small gradient change in signal. Due to this fact there are no absolute values for amplitude damping or the phase shift shown here but only relative ones.
In Fig. 3 a camera picture taken by the imaging device before starting a measurement is displayed alongside with a comparison of the obtained raw data images using a device working at about 80 GHz and also at slightly below 100 GHz. Besides the fact, that imaging done at about 100 GHz is showing a 20% better resolution than imaging at 80 GHz (derived from a comparison of the Siemens-star images - therefore the new generation of imaging device is utilizing the higher frequency), the image also indicates one of the strong advantages of mm-wave imaging over e.g. x-ray. In the figure even the powder samples show up in the raw data. No complicated filter configuration has to be adjusted in order to be able to see these materials (displayed powder samples consist of different amounts of flour and sugar). In addition to the above mentioned and improved resolution in the classical physical definition depended on the utilized wavelength, the clever setup of the imaging device is capable of also capturing near field effects. Hereby structures well below the classical resolution limit can be imaged.

An example of this is shown in Fig. 4. Here a Cu-Wire with 200 µm diameter is hidden below a paper structure. Even though there is no direct image information of the wire to be seen, the diffraction pattern around its slim structure indicates, that there is something underneath. This feature might especially be of interest when trying to detect hidden wiring inside of pieces of mail or even when trying to detect contamination in food products etc. The influence of the material on the image quality is displayed in Fig. 5. Here a test pattern constructed of a Siemens-Star, a diagonal slit pattern and a pattern similar to that of a
chessboard is imaged (bulk material being the one colour and material voids being the other). For one test pattern the material is plastic (left) and the other one is made from metal.

![Fig. 5. Measurements of a 25 cm x 25 cm test pattern made from (left side) plastic and (right side) metal. Differences in material properties result in stronger disturbances due to strong diffraction of the electromagnetic waves on well-defined metallic boundaries. Colour code shows normalized amplitude.]

Besides being able to see the difference between a reflecting (metal) and almost transparent (plastic) bulk material, there is also a big difference in imaging quality due to multiple edge diffraction inferences. Because this effect is much stronger in metal, many small metallic structures close to each other are more complicated to identify. Even correcting for antenna characteristics is not able to cope with these multiple interference patterns and lead to a significantly better image. Another feature, which is shown in Fig. 6, is the sensitivity towards water. As long as there is no fully closed water surface, various amounts of water content can be detected – depended on the surrounding material.

![Fig. 6. The figures show a sequence of measurements of a leaf over several hours. The measurements visualize the dehydration process of biological materials.]

V OUTLOOK

Driven by enhanced requirements of industrial customers, increasing measurement speed is essential for the successful implementation of the imaging system in industrial applications. To accelerate the test process, the rotation frequency of the discs platform must be increased. This results in a larger surface per time proportion which can be tested. One mechanical problem restricting the disc’s rotation speed is that the mass distribution of the HF components on the discs platform is inhomogeneous. Through the square dependence from centrifugal force by rotation frequency, the force to the discs will rise up significantly. To solve this problem, a transfer of most of HF-components from the rotating to the static part of the system is an obvious approach. The necessary HF signal can be inducted by
special rotary waveguide joints for the W-band. An appropriate rotary joint for W-band is available from SPINNER GmbH which has an effective usable bandwidth of 4 GHz. Additional to the possible improvement described previously; there are much more interesting capabilities. The measurement throughput can be increased by incrementing the number of antenna elements ($N$) on each rotating disc [3]. This concept will accelerate the test process linear by $N$. For this purpose it is important to suppress crosstalk between the antenna elements, otherwise the dynamic range of measurement will decrease. To ensure sufficient channel decoupling, frequency multiplexing is introduced to the system. As an example of four antenna pairs, a sensible frequency plan is shown in Fig 7.

![Fig. 7. Possible frequency plan for four channel CW system in W-band.](image)

In principle, four baseband channels can be realized in form of time or frequency division multiplexing by a Direct Digital Synthesis (DDS) concept. After up-converting the combined baseband signals to W-band, the resulting millimetre wave signal can be transferred through the rotary joint to rotating module, which must not necessarily form a disc. The signal is split by a two stage power divider as shown in Fig. 8, resulting in an insertion loss of 6 dB within each path. To select the frequency bands for each antenna element, a frequency selection in form of bandpass filters in front of the antennas is required. After being uncoupled through the transmitting antenna and interacting with the DUT, the HF-signals will couple in the antennas on the receiver module. The received signals from all four antennas are combined by a passive network analogue to the one used on the transmitter side and coupled to the static part of the system by another rotary joint.

![Fig. 8. Possible conceptual construction with four antenna pairs](image)

Standing wave effects, caused by insufficient matching of the waveguide splitters and the strong out-of-band reflections of the filters need to be suppressed. A solution for this problem is the usage of power dividers with good isolation of the output ports. In this case the wave, which is reflected at the other three bandpass filters, will be transmitted back to the HF source or better to an isolator in front of it [3]. For increasing the measurement
dynamic range even further, it could be considered to add additionally bandpass filter on the receiver side. Regardless of whether, there are high requirements on the bandpass filters based on the small frequency spacing of the HF signals. To achieve the desired performance, the filter slope must be very high and furthermore the insertion loss at centre frequency should be as small as possible. Due to the high Q-factor of hollow metal waveguides, this filter can be realized with cross coupled- or iris-filters in split-block-technology. As shown in Fig. 9 more than 40 dB channel decoupling have been obtained in a first filter prototype with an insertion loss as low as 3 dB.

Fig. 9. Developed narrow band waveguide iris-filter with 3 dB insertion loss and >40 dB suppression of neighbour channel

VI SUMMARY

The paper demonstrated that fast and low-cost mm-wave scanners can be realized with components on the shelf (cots). One application for the imaging system is incoming mail inspection in small offices, embassies or similar institutions. Further applications like online monitoring of production processes are possible due to the scalability and flexibility of the presented radar concept. Especially for the inspection applications in the food industry mm-wave scanners offer an alternative to classic inspection systems based on optical and x-ray systems. New system concepts offer the possibility to speed up the scanning rate and improve the performance of mechanical rotating systems.

References