Development and Design of Broadband Pulse-Based Transceiver Systems at THz Frequencies Final Project Report

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***Abstract*—This report presents the interim results of my work on the development and design of broadband pulse-based transceiver system at THz frequencies. This approach utilizes high bandwidth and can thus provide precise measurements for a variety of application scenarios, including the increase in resource efficiency in the manufacturing of energy-intensive products through inline sensor material thickness control.**
Although the entire system has not yet been precisely characterized as a whole due to the long production cycle of the MMICs, significant progress has been made in both fundamental research and system design. For the broadband pulse generation, the expected frequency components were verified up to 500 GHz, and a transient pulse in the picosecond bandwidth range was reconstructed from the spectrum, proving the feasibility of the PIN-diode approach.
Keywords*— terahertz (THz), SiGe, transceiver, pulse, PIN diode, dual-comb, high resolution, precision measurements.

I. Pulse-Based Transceiver Systems

My current research comprises several key tasks: THz pulse generation, design of the transceiver including the realization of a receiving mixer for the dual-comb approach and the PCB design. The near-term plan also includes design and tuning of signal sources to frequencies with fixed frequency difference, as well as measurement and evaluation of the results.

A. THz Pulse Generation

When investigating THz pulse generation, two different approaches are considered. The transistor-based approach utilizes harmonics generated by switching an extremely high current from one path to another in a differential transistor circuit, similar to a differential cascode amplifier.
The PIN diode approach is based on the phenomenon of reverse recovery when switching a current in a short period of time. Instead of following a sinusoidal curve, the current through the diode abruptly drops to zero as soon as all the carriers stored in the I-region in the forward conduction are depleted in the reverse conduction mode and the diode cannot sustain the current. If a sharp edge is derived, e.g., by an inductive load, the values of the slope forming a pulse are obtained. This is a very promising approach as it does not require a complex architecture and remains passive except for the DC bias if a differential pulse is desired, thus it is energy-efficient, and the only space-consuming element is the planar coil.

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B. Transceiver Concept

For the transceiver, a bistatic system approach was chosen to allow separate receiver and transmitter MMIC characterization using existing sensors. Both MMICs include a PIN diode-based pulse generating circuit and an antenna, while the receiver additionally contains a mixer for the dual-comb approach. The dual-comb approach describes mixing two frequency domain combs with a difference in tone spacing. Based on the Fourier transformation, it corresponds to mixing time domain pulse trains with a slight difference in repetition rate, resulting in broadened pulses and thus a low-frequency comb. The resulting signal retains the information of the original combs but can be sampled much more easily.

C. Current Results

For the THz pulse generation, the transistor-based circuit was realized in IHP 130 nm SG13G3 technology and characterized up to 110 GHz. Despite being limited by equipment availability, expected frequency components were confirmed in this range, providing the proof of concept. A modified version with new pad configuration to extend the possible frequency range and enable transient pulse reconstruction is considered. The PIN diodes are available in Infineon's B11 and B12HFC SiGe technology, but their reverse recovery and switching characteristics have only been described by physical models. To investigate their behavior, several test circuits were created, containing diodes of different sizes, with and without inductive load and based on different avaliable models. The MMICs were characterized in the frequency domain up to 500 GHz using multiple probes and UXA extenders. The spectra were merged, and the expected harmonics were confirmed across the entire measured frequency range, enabling THz pulse reconstruction from the spectra assuming zero phase difference. These results led to the selection of the PIN diode approach for the transceiver system, designed in Infineon's B11HFC 130 nm SiGe BiCMOS technology. The first transmitter-receiver combination is implemented with folded dipole antennas designed for a center frequency of 300 GHz. With the Si lenses purchased and the PCBs ready for production, the first system measurements are scheduled within the next few months. Although the lower antenna cutoff frequency is too high to radiate all relevant pulse frequency components, it will serve as a proof of concept for a limited frequency range. The second and third advanced versions using the same technology are already in production. The second version retains the idea of direct pulse radiation but offers an innovative broadband antenna with a cutoff frequency of only 50 GHz. The passive diode ring mixer used in the first approach is provided with additional diode path bias to maintain sufficient voltage amplitude of the IF signal. The third system addresses the problem that the strongest frequency components between 5 GHz and 50 GHz are still lost due to the antenna characteristics. An additional diode mixer converts the generated pulse bandwidth to the frequency range around the local oscillator frequency of 160 GHz in the transmitter and back in the receiver, allowing all the relevant frequency components to be radiated. The LO signal is generated on-chip from a low power 40 GHz input.

D. Future Work

For the system evaluation, lenses will be attached to the chip through an opening in the PCB to reduce substrate modes and improve the antenna directivity. The radiation occurs through the MMIC, the PCB opening, and the lens. In the first version of the systems, the input signals for the pulse generators are provided off-chip. One of the main challenges for the future versions is to realize on-chip signal generation. These frequencies determine the repetition rates of the pulses and thus their difference, which is crucial for the dual-comb approach. Once the off-chip frequency adjustment is resolved and the first IF comb is measured, the range and thickness measurement can be performed, using signal processing to evaluate the results. The new transceiver MMICs are expected to arrive within the next year, so I am optimistic to achieve a functional system with room for improvement.

II. Project Work

My work on fundamental PIN diode research was conducted as part of the Terahertz.NRW project. Specifically, I was involved in work package 3.3 Transceiver Technologies, Innovative Materials and Components for Future THz Transceivers, where the focus is on fundamental research that will lay the foundation for future THz systems. Moving towards full system and industrial application, I am now working on the TIGER project, which aims to create a robust and cost-effective fully integrated THz inline sensor, positioning THz sensing as a key sensor technology to future “smart factories”. My task in this project is the design of MMIC and PCB transceiver system components.

III. Conclusion

This report presented the research conducted on the design of a broadband pulse-based THz transceiver. Two realized approaches for pulse generation and transceiver concepts were introduced. The PIN diode pulse generator provides proof of concept for low-area, low-energy, and low-cost solution, with the frequency components verified up to 500 GHz. The main short-term goal of my research is to create a first working prototype of the transceiver and then to optimize its performance while completing my Ph.D. I will deepen my knowledge in the areas of signal synchronization and processing to be able to perform the initial measurements and evaluate the results, and I look forward to challenges ahead.

IV. Acknowledgement

This research relies heavily on the fabrication of new components and breakout circuits. Multiple approaches need to be compared, and several manufacturing iterations are required to realize and optimize the fully integrated system to provide the most cost-effective solution for the industry. Therefore, this work requires financial support to be successful.

Receiving the MTT-S Scholarship Award has provided a great help in achieving my research goals for the next few years in combination with our project funding. The award funds were used to purchase collimating silicon lenses for THz radiation, which are essential for future system testing, as well as to partially fund the transceiver system MMICs and PCBs.

An even more appreciated part of the award was the opportunity to attend an MTT-S conference. Even though I could not be at the IMS2024 and meet other award recipients, which would definitely have been an inspiring experience, I was more than grateful to attend EuMW2024 instead. This week-long event proved to be extremely valuable for further development in my field of research. Every day, I took part in numerous workshops and gathered knowledge and ideas for my future work. However, the most rewarding aspect for me was the exchange within the scientific community. Comments, suggestions, and even criticism have contributed significantly to my progress. This event led to the establishment of new contacts and valuable collaborations, which have been instrumental in advancing my research.

V. Future Plans and Career in RF

This year, I successfully defended my master’s thesis in the field of integrated circuit design as part of the TopING program. TopING is the fast-track Ph.D. program of the Faculty of Electrical Engineering and Information Technology at the Ruhr-University Bochum. It offers selected students the opportunity to work on their doctoral thesis as a research assistant during their master’s studies. With over three years of experience working as a student and research assistant at the Chair for Integrated Systems, and with my master’s degree now completed, I am excited to dedicate myself full-time to research. Currently, I am two years into my Ph.D. program and will spend the next four years pursuing it. I thoroughly enjoy the challenges and opportunities of scientific research, so I would be happy to stay on as a postdoc afterward if I get the chance. Apart from my research project, I find fulfillment in my responsibility being a bachelor’s thesis supervisor and a teaching assistant for Prof. Pohl’s electronics course that initially inspired my interest in this field years ago.

The recognition from the MTT-S Scholarship has reinforced my confidence in the significance and potential of my research and provided me with the resources to further explore this field. I am now more certain than ever that I am on the right path and look forward to meeting the challenges and achieving my research goals.