Simplified FMCW Radars Implementation for Guided Terahertz Reflectometry Sensing

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***Abstract*—The implementation of a guided FMCW reflectometry transceiver is proposed and investigated through two millimeter-wave FMCW radar units based on different technologies. Electromagnetic simulations, corroborated by imaging tests, assessed the capabilities of such sensing systems with the highlight of their respective advantages and drawbacks. Both 3D electromagnetic simulations and raster scan images are performed to investigate quantitatively the propagation behaviors including the coupling capabilities, dynamic range limitations, beam profiles and induced artefacts of the guided FMCW reflectometry system. The achieved simplified architecture ensures suitable performances while the distance sensing capability of the FMCW radar is improved up to 60 -80 cm. Simple hardware enhancement is as well assessed on the systems to provide drastic lateral resolution improvement.**

I. INTRODUCTION

THANKS to the advances of semiconductor technologies (both Si-based and III-V based technologies), the operating frequency and performances of ultra-fast electronic devices and systems continues to increase. Up to date, fully integrated Frequency Modulated Continuous Waves (FMCW) Radar systems in the terahertz domain are commercially available providing cost-effective solutions for versatile systems implementation. Apart from simple object detection and positioning applications, terahertz FMCW radar systems have been widely implemented through classical quasi-optical scanning systems to perform imaging measurements for art-painting diagnosis [1][2], or for quality control and defects detection in the automotive and aeronautics industries [3][4] amongst other applicative fields.

II. RESULTS

Targeting simplification and performances optimization compared to the existing terahertz guided probing systems, this work reports on the first implementation of guided FMCW radar reflectometry probe for sensing and imaging [5]. Instead of widely used lenses or parabolic mirrors in quasi-optical configurations, a single terahertz dielectric waveguide is used to couple signals between the radar transceiver module and the sample, thus simplifying drastically the experimental setup toward an optic-free solution and reducing the related alignment requirements while allowing the development of compact sensors. As a simple optimization, a foam support, acting as well as terahertz absorber, is placed in the vicinity of the coupling area to neutralize the reflected parasitic signals induced by the non-coupled echoes, resulting in a significant signal improvement.

Compared to Continuous Wave (CW) guided probing systems, one of the main advantages granted by the use of FMCW Radars lies in its depth sensing capability, and so its ability to differentiate the various contributions to the received signal thanks to its embedded phase information. The discrimination between the reflected signals generated along the waveguide and at its probing-end ensures a proper knowledge concerning the origins of the detected signals and accounts for an improved signal to noise ratio for sensing applications.

This innovative approach is demonstrated on two radar transceivers based on distinct technological approaches : the high-performance III-V based 100 GHz SynView unit as a reference system and a compact, PCB-integrated 122 GHz transceiver developed by Silicon-Radar GMBH [6] as a low-cost solution. Two different quasi mono-static transceivers emissions geometries are therefore tested to demonstrate the adaptability and universality of this implementation scheme via the deployment on a conical horn antenna with the SynView unit and the dual RX/TX patch antenna design with the Silicon-Radar integrated chip. In correlation with those emissions front-end and the market availability, the suitability of the selected 6-mm-diameter dielectric thin wall hollow-core waveguide to ensure anti-resonant guiding mechanism is as well assessed.

Both 3D electromagnetic simulations in correlation with raster scan images on test charts are performed to investigate the capabilities of the guided FMCW reflectometry systems.

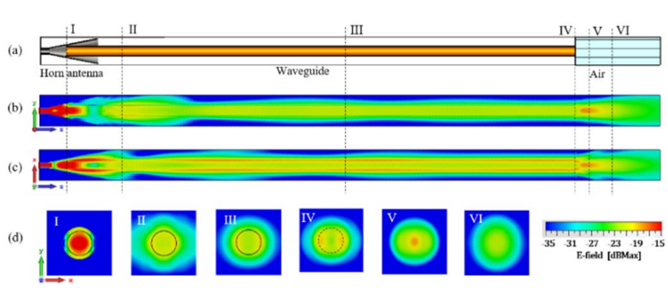


Fig. 1. Simulated propagation profile along the 100GHz guided FMCW SynView transceiver with normal electric field magnitude profile cuts along the waveguide.

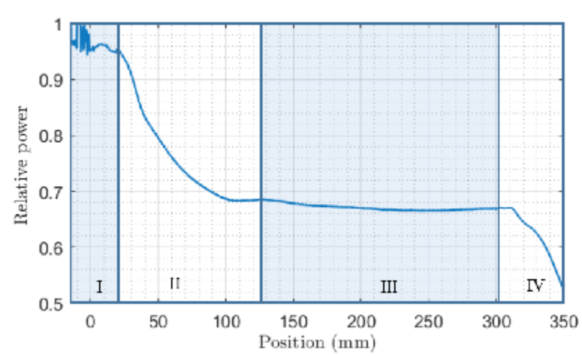
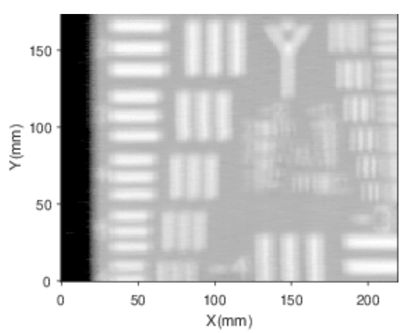


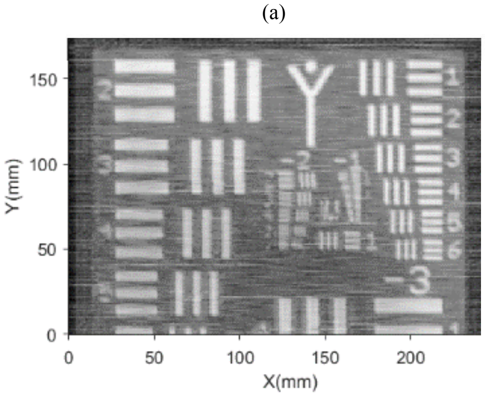
Fig. 2. Simulation of the enclosed power as a function of the propagation distance revealing the coupling ratio of 0.68 when reaching guided steady-state, for the 100 GHz SynView guided module.

Quantitative analysis of the simulated propagation proprieties (see Fig. 1 for the 100GHz SynView transceiver) provides insight on the coupling efficiency (see Fig 2.), the achievable sensing dynamics as well as the expected optical resolution and induced imaging artifacts via the investigation of the end-of-guide beam profile (see Fig. 1(d)). A proper and consistent propagation scheme have been retrieved for the 100GHz reference system as displayed in Figure 1, while a less predictable behavior has been witnessed for the simulations of the 122 GHz silicon radar low cost unit due to its small scale bi-static dual patch antenna design, inducing a 1.5 mm decentering of the emission and reception points, with respect to the waveguide's axis. More precisely, a loss of symmetry, in the guiding and emission profiles, are witnessed for this geometry, and lower coupling coefficient is reached, owing to the wide emission pattern of the patch antenna design.

To supplement those results, a confrontation of those simulations with the performed raster-scan images of a test chart depicted a good correlation with the simulations in term of resolution, mainly limited by the lateral dimension of the waveguide. Similarly, the impact of the beam profile induced artifacts on the imaging capabilities for both systems have been highlighted; especially with the appearance of ghosting artifacts, as depicted in Figure 3 (a), for the reference transceiver due to the radially separated 2 main amplitude lobe emission profile, noticeable on the waveguide output electric field magnitude profile on Figure 1 (d) IV.



(a)



(b)

Fig. 3. Raster scan image of a test chart, using the 100GHz bare SynView guided transceiver and (b) with the implementation of the improvement resolution solid immersion lens

To further address the limited resolution as well as the guiding induced artifacts, inherent to the waveguide's geometry, while avoiding heavy configuration with optical components, the insertion of an end-of-waveguide solid immersion lens is demonstrated. Thanks to the selected low

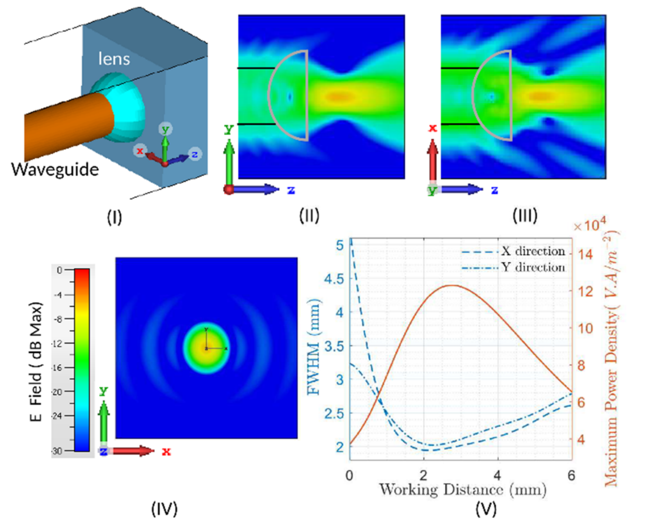


Fig. 4. Electromagnetic simulations with solid immersion HDPE hemi-spherical lens: (I) implementation diagram of the guide termination, electric field magnitude profile (II) in z-y plan, (III) z-x plan and (IV) x-y cut in the best imaging plan, (V) evolution of the beam diameter and maximum power density with respect to the working distance.

refractive index hemispherical geometry of the lenses, high Numerical Aperture focusing is achieved, as depicted on Figure 4, to provide a high resolution imaging system (see Fig. 3 (b)) with millimetric working distance and 2mm lateral resolution while avoiding unwanted significant signal reflection.

III. Summary

The feasibility of the guided terahertz FMCW reflectometry system is demonstrated as a low-cost solution where a polymer pipe waveguide is used to ensure the single coupling channel to reach a compact and simplified guided probing unit. An adequate coupling efficiency between the transceiver device and the waveguide is achieved in a simplified configuration while imaging results corroborate the conducted electromagnetic simulations. Intrinsically limited by the waveguide's dimension, further improvements on the imaging resolution have been investigated through the implementation of solid immersion lenses.

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