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Applications of Terahertz FMCW Radar Reflectometry with Plastic Waveguide †

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Abstract

This paper presents a compact 122 GHz Terahertz FMCW radar using a plastic hollow-core dielectric waveguide for non-destructive testing. The guided approach simplifies the system, avoiding complex free-space optics and alignment, while improving signal-to-noise ratio by isolating endpoint reflections from internal ones. Various configurations, including solid immersion lenses, enhance spatial resolution and imaging capabilities. Experiments combine 3D electromagnetic simulations and raster-scanning to image fine details and detect subsurface defects. Applications span aerospace, automotive, and art conservation. Results demonstrate guided FMCW radar as a cost-effective, portable, and reliable alternative to traditional free-space setups, enabling broader, practical implementation across industries.

Keywords: Terahertz; FMCW radar; plastic waveguide; non-destructive testing; reflectometry; imaging; millimeter-wave; resolution enhancement; guided waves

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1. Introduction

Terahertz (THz) waves have attracted growing attention for their numerous imaging applications [1], ranging from material characterization to security screening and cultural heritage preservation [2]. Among the different THz imaging technologies, Frequency Modulated Continuous Wave (FMCW) radar has demonstrated particular relevance for industrial inspection and composite material analysis, offering high resolution and penetration depth combined with compact and cost-effective architectures [3–5]. Traditionally, THz FMCW imaging systems operate in the far field, employing Gaussian beams shaped by lenses or mirrors to illuminate and scan the sample. In parallel, several studies have explored the use of THz waveguides as an alternative propagation medium, enabling guided delivery of THz radiation directly to the inspection site. Previous work has shown the feasibility of imaging using continuous-wave (CW) sources coupled to metallic waveguides [6], as well as the implementation of time-domain reflectometry and imaging with pulsed systems using dual-antenna configurations and dielectric guides [7]. Building on these advances, it is also possible to perform FMCW radar imaging in reflection mode through waveguides, producing high-quality images as demonstrated in earlier research [8]. In this work, we propose a new integration of this concept, combining a compact 3D-printed hollow-core dielectric waveguide with a 122 GHz FMCW radar module, forming a self-contained sensing unit. This approach eliminates complex optical alignment, improves measurement robustness, and is applied here to the non-destructive inspection of composite materials.

2. Materials and Methods

The setup, as illustrated in Figure 1, consists of a *Siliconradar* TRA_120_002 FMCW radar operating at 122 GHz, without collimator or lens, and with a 6 GHz bandwidth. The radar is coupled to a dielectric waveguide with a diameter of 5 mm and a length of 218 mm. The waveguide is held in place by a 3D-printed mount providing regular support along its length. The wave is transmitted along the waveguide to its terminal end, where the object under inspection is positioned. The waveguide is passed through an opening in absorbing foam to reduce the effect of uncoupled free-space radiation that could propagate outside the guide and introduce noise.

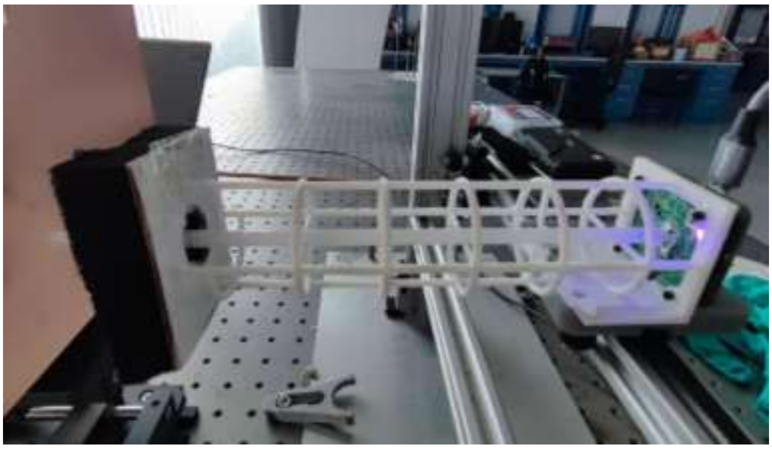


Figure 1. Photography of the experiment. The FMCW radar is shown on the right, the waveguide and its holder in the middle, and the object on the left.

The first experiment involves positioning the probe in front of a reference mirror to obtain the baseline measurement, as illustrated in Figure 2, which shows a 60 dB peak at the 250 mm position.

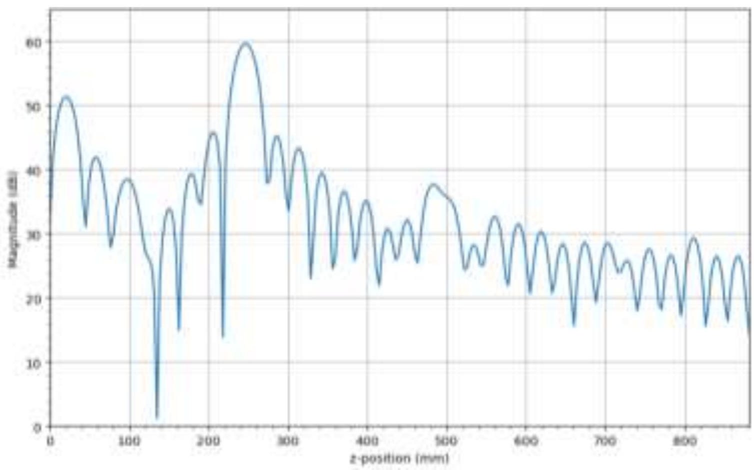


Figure 2. Reference signal reflected when the probe is in contact with a reference mirror. A 60 dB peak can be observed at the 250 mm position.

3. Discussion

Following this preliminary work, a subsequent study was conducted to assess the impact of the probe–sample distance on the reflected signal. Previous studies have shown that the wave undergoes significant diffraction at the waveguide termination; this measurement allows for better calibration of the working distance for such a setup. The local maxima associated with the apparent mirror position in the previous graphs were used to perform an exponential fit.

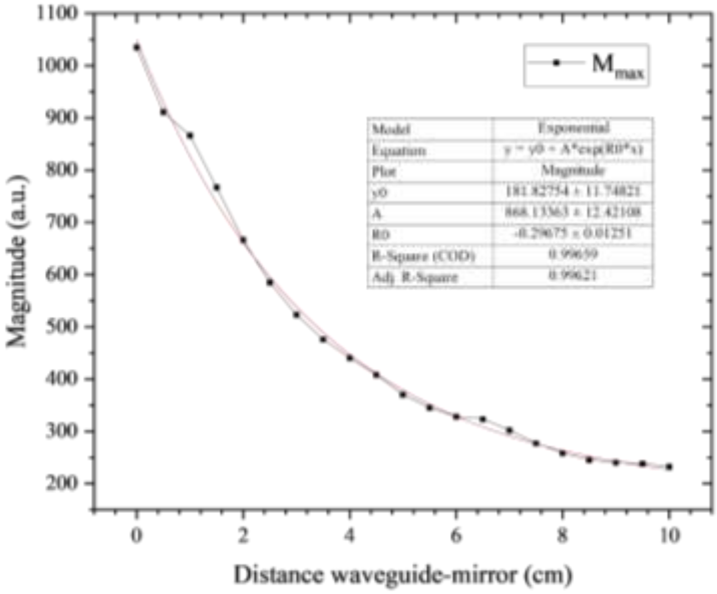
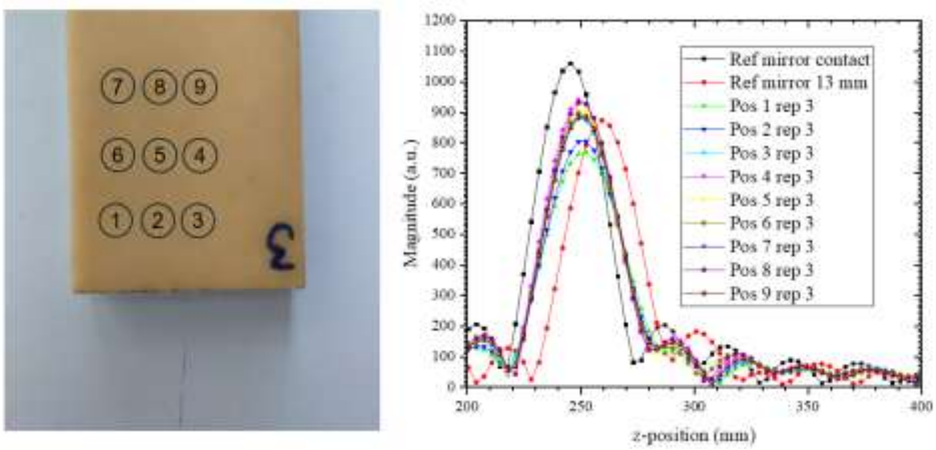


Figure 3. The local maxima associated with the apparent position of the mirror from the previous graphs were used to perform an exponential fit.

Following these calibration experiments, measurements were carried out on a GFRP composite material representative of the applications targeted by this technique. The different measurement points, shown in Figure 4a, correspond to the signals presented in Figure 4b.



(**a**) (**b**)

Figure 4. (**a**) Fiberglass composite material under test, (**b**) Magnitude of the main peak corresponds to the signal of each point.

To validate the reproducibility of these results, the experiments were repeated several times. As shown in Figure 5, the measurements performed on multiple occasions yield comparable results.

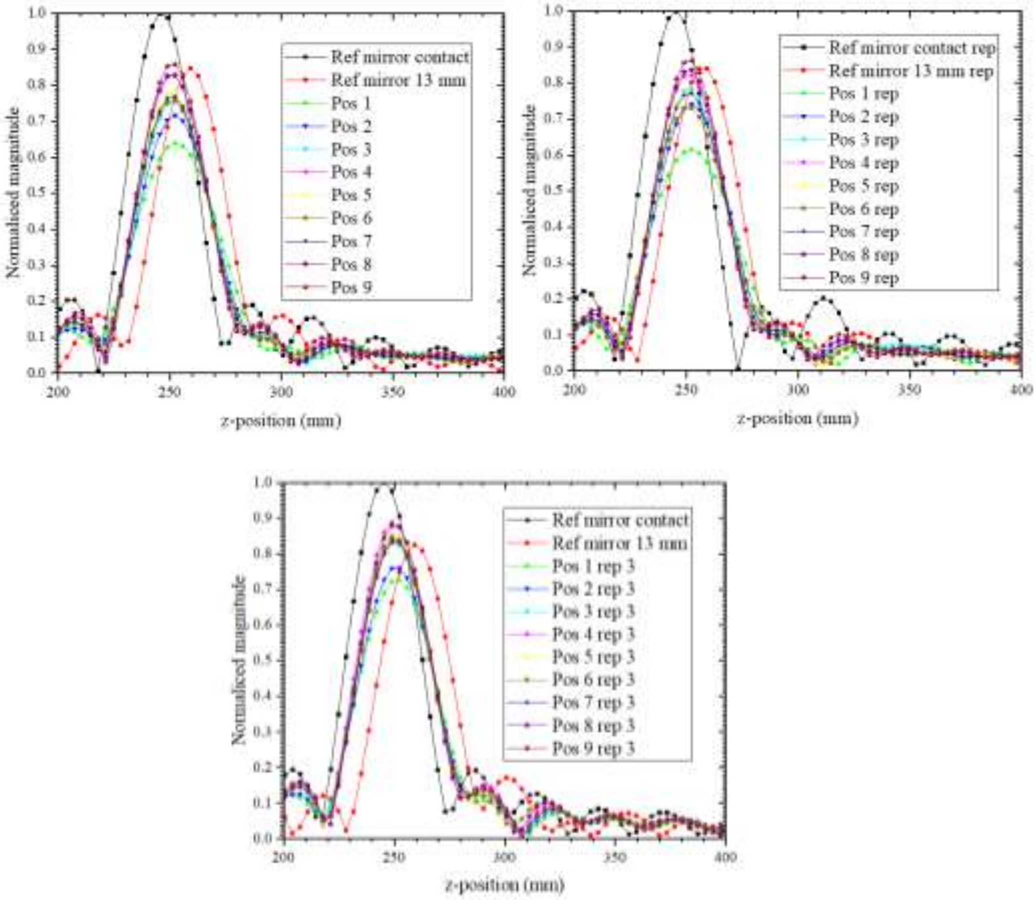


Figure 5. Several measurements to check the reproducibility of the experiment results.

4. Conclusions

This work has demonstrated the feasibility and advantages of integrating a compact 122 GHz FMCW radar with a 3D-printed hollow-core plastic dielectric waveguide for non-destructive testing applications. By replacing conventional free-space optical components with a guided-wave architecture, the system achieves a significant reduction in complexity, eliminating the need for precise optical alignment while enhancing portability and robustness. The incorporation of an absorbing foam interface further mitigates spurious free-space radiation, thereby enhancing the signal-to-noise ratio and ensuring that the measured reflections predominantly arise from the targeted inspection area.

A preliminary calibration campaign, involving measurements against a reference mirror at varying probe–sample distances, allowed for a precise characterization of the diffraction and propagation behavior at the waveguide termination. This step was essential to establish an optimal operational range for accurate measurements and to model the distance-dependent reflection amplitude through exponential fitting.

Subsequent experiments on a GFRP composite material—representative of aerospace and other industrial applications—validated the system's capacity to detect and quantify variations in reflected signals across multiple points on the sample surface. The reproducibility of the measurements, confirmed through repeated acquisitions under identical conditions, underscores the reliability of the approach for practical inspection scenarios.

The proposed architecture offers several key benefits over traditional free-space FMCW radar setups: (i) reduced bulk and cost by avoiding lenses and mirrors, (ii) improved measurement fidelity through guided delivery of the signal to the region of interest, and (iii) versatility in adapting the waveguide geometry to the constraints of complex inspection environments. Furthermore, the compatibility with solid immersion lenses or other focusing elements opens the door to spatial resolution enhancement without fundamentally altering the system design.

These results highlight the strong potential of guided FMCW radar reflectometry as a portable, cost-effective, and application-oriented alternative to established THz imaging techniques. Future work will focus on extending the method to more complex geometries, integrating multi-channel guided systems for faster scanning, and exploring advanced signal processing techniques for defect classification. The approach presented here could find wide applicability across aerospace, automotive, civil engineering, and cultural heritage conservation, supporting the broader adoption of Terahertz sensing technologies in field-deployable inspection systems.

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