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Harnessing Frequency Diversity for Improved Holographic Imaging Systems

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Abstract—**This study investigates the impact of varying the illuminating frequency spectrum over time in a 340 GHz FMCW radar system with a holographic setup. Experiments using a corner cube reflector explored the behavior of spatially varying frequency-dependent field patterns across bandwidths ranging from 326 to 356 GHz. Findings suggest that varying the illuminating frequency spectrum over time can capture more spatial information from the target than using the radar's entire bandwidth allowing for improved target discrimination and imaging capabilities in holographic radar systems.**

I. Introduction

Submillimeter-wave imaging an effective modality for security screening, particularly in discerning hidden objects as it can penetrate through optically opaque materials, including most clothing, to provide visibility in challenging scenarios. One submillimeter-wave imaging technique is frequency-diverse imaging, which manipulates electromagnetic waves across a range of frequencies to extract information about a scene or object of interest. An example is [1], where submillimeter-wave imaging was performed on a wide band (220-330 GHz) using dispersive holograms and deep neural networks (NNs).

Frequency-diverse imaging, which uses a wide-band submillimeter-wave signal, eliminates the need for traditional beam steering methods, potentially offering advantages in system simplicity and efficiency [2]. Image reconstruction techniques are then applied to process the complex signals, enabling the restoration of the reflectivity distribution within the region of interest (RoI). This approach not only facilitates high-resolution imaging and penetration through optically opaque materials but also allows for imaging frame rates independent of physical beam scanning, dependent only on frequency sweep time and computational power at the system back end [3].

In this work, we present the development and experimental results of a submillimeter-wave standoff imaging system using frequency-diverse holograms and a 340 GHz Frequency Modulated Continuous Wave (FMCW) radar.

II. Imaging System

The imaging system uses a single transceiver and a frequency-diverse hologram to illuminate the RoI. The RF subsystem consists of a direct digital synthesizer (DDS) which generates a frequency modulated (FM) linear chirp from 901 MHz to 1370 MHz. The chirp signal undergoes heterodyne upconversion, amplification, doubling, and filtering to the X-band spanning 10.2 to 11.1 GHz. This waveform is fed to a submillimeter-wave transceiver unit, which multiplies the X-band chirp by 32, expanding the bandwidth to 340 +- 16 GHz. The submillimeter-wave transceiver unit is characterized and presented in detail in [4].

A custom spline-profile circular horn antenna at the output of the transceiver unit illuminates a hyperbolic collimating lens which is then directed to a hologram. The lens and hologram are made of Rexolite and create frequency-diverse radiation patterns over a 0.15 m × 0.15 m region at a 1-meter distance [5]. Target backscatter is coupled back to the transceiver through the same optics and the signal is mixed with the outgoing directly to baseband. Then the signal is band pass filtered at 9–15 MHz and amplified prior to sampling with a high speed ADC.

III. FMCW Radar With Dispersive Hologram

FMCW radar emits a chirp signal to a target, and upon encountering an object, the signal is reflected back to the radar receiver. The transmitted signal interacts with various surfaces within the scene, and each surface or object reflects the radar signal differently at different frequencies, contributing to a distinctive frequency response pattern. As the illuminating frequency is swept over multiple frequencies, the reflectivity information from the region of interest is encoded into the wide-band back-reflected signal [6]. In order to add an additional layer of sophistication, a frequency-diverse hologram has been engineered to construct spatially varying, frequency-dependent field patterns over the bandwidth of the radar.

Holographic techniques inherently involve spatial encoding of information. In the context of FMCW radars, this spatial encoding can be aligned with the variety of frequencies introduced by the radar system. The combination of holography and FMCW radar's wide bandwidth and frequency resolution allows for a more comprehensive encoding of spatial and frequency information, leading to advanced radar imaging. A dispersive phase hologram consists of multiple discretized phase levels with multi-wavelength elevation. As the illuminating frequency varies, the phase shifts from individual surfaces accumulate differently, resulting in spatially varying radiation patterns at the RoI [7].

In FMCW radar, altering the sweep bandwidth involves adjusting the range of frequencies over which the radar signal is modulated. This choice significantly impacts the quantity and quality of information obtained from the Field of View. By employing a smaller bandwidth, such as 2.5 GHz, instead of the full bandwidth of 30 GHz, we can acquire more spatial information from the target. While this choice may lead to a reduction in range resolution $dr = \frac{c}{(2B)}$, it enables the radar system to discern finer spatial details, unaffected by the bandwidth but determined by the wavelength. In imaging applications, prioritizing spatial information over range resolution enhances overall imaging capabilities, despite the trade-off.

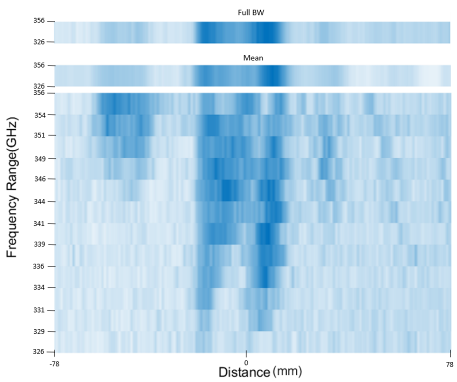

Fig. 1. Variation of Field pattern across different bandwidths in X plane

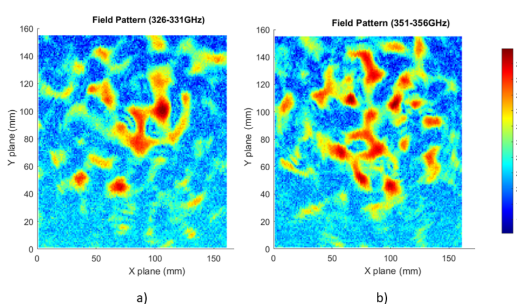

Fig. 2. Field patterns in X-Y plane a) 326-331GHz b) 351-356GHz

IV. Experimental Results

Experiments were carried out with the imaging system described in Section 2. The experiments used an 25.4 mm diameter corner cube reflector target, which was placed 1 m from the hologram. The corner cube was then moved in a plane transverse to the transceiver optical axis with bandwidth limited to 2.5 GHz: 326 - 326+2.5 GHz. This experiment was repeated 12 times in increases bandwidth centers up to 356 GHz. The sampled transceiver time-domain response was windowed, transformed to the frequency domain, and normalized. The amplitude of the frequency domain peak corresponding to a 1-meter range was captured in each position, and the results are presented in Figure 1. For comparison, the FMCW range data from the full 326 - 356GHz is displayed in the top subpanel labeled "Full BW". Moreover, the mean of all the data in every bandwidth was also calculated and is displayed in the subpanel labeled "Mean". Similarly, two more experiments were carried out, scanning the X and Y planes in two different frequency-limited bands. The results of the experiment at 326-331 GHz and 351-356 GHz are shown in Figure 2, a) and b) respectively.

From the Figure 1, frequency diversity over spatially varying frequency-dependent field patterns can be observed over different band-limited stripes. Moreover, differences in field patterns in Figure 2 further illustrates the spatial diversity in the field over different frequency bands.

V. Summary

In summary, different sweep bandwidths were tested in a 340-GHz FMCW radar system equipped with a hologram. The research reveals that by varying the illuminating frequency spectrum over time can capture more spatial information from the target over illumination with full bandwidth of the radar. This finding of expanded frequency diversity will allow radar to detect subtle differences in object responses, leading to better target discrimination and imaging capabilities.

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