Quasioptical Time-Delay Multiplexing for a Terahertz Imaging Radar

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Abstract- **Time-delay multiplexing is a method where the frame rate of a single-transceiver terahertz imaging radar can be doubled by splitting the transmitted beam into two beams of orthogonal polarization, and then scanning the beams over two separate regions of a target simultaneously. We previously demonstrated multiplexing at 4 m standoff distances in a 670 GHz imaging radar, using waveguide components to split the beams and rotate their polarization. However, significant ohmic losses through the waveguide components were measured, and finite transmit/receive coupling contributed to a substantial dynamic range reduction. In this contribution we demonstrate radar multiplexing in a 670 GHz imaging radar operating at longer standoff distances of 25 m, and we present an all-quasioptical approach for beam splitting and polarization rotation. By eliminating the extra waveguide components, we have achieved a frame rate doubling from 0.5 to 1 Hz with negligible signal attenuation and transmit/receive leakage. Moreover the same multiplexing technique can be used to send two signals with orthogonal polarizations to the same target spot and obtain the full polarization matrix.**

I. INTRODUCTION

The frequency-modulated continuous-wave (FMCW) radar technique at high frequencies has been demonstrated to be a powerful system to detect concealed objects on a person [1]. The NASA Jet Propulsion Laboratory's imaging radar operates at 670 GHz with a nearly 30 GHz bandwidth that enables sub-centimeter range resolution. Since the system concept was reported in [1] and good quality through-clothes images were obtained, a significant engineering effort has been made to shorten the image acquisition time. In this contribution, we describe the main developments in the radar optics that have been implemented to accelerate the imaging frame rate.

In the 4 m standoff prototype radar, an image was acquired by mechanically rotating the entire radar platform, which translated in acquisition times on the order of several minutes. The current imaging radar implementation uses a fast rotating subreflecting mirror instead, enabling frame rates as high as 1 Hz. The radar optics have already been described in detail [2], [3]. Figure 1 shows a photograph of the optics: a 1 m diameter ellipsoidal reflector focuses the beam to a (two-way) spot size of about 1 cm at 25 m standoff. The antenna system consists of a confocal geometry having a magnification of 10. This large magnification translates into smaller secondary optics necessary for the rapid scan. The secondary reflector is illuminated by a collimated beam that reflects from a 13 cm diameter tilting flat mirror used to scan the radar beam over about ±2.5° in elevation and azimuth. Taking into account the system magnification, this translates to a field of view of ±25 cm at the standoff range of 25 m. The antenna system has been optimized to have minimal beam aberrations over the field of view. The beam profiles over the field of view have been verified and presented in [3]. Several system bottlenecks have also been overcome achieve 1 Hz imaging rates. The main ones are the acceleration of the scanning mirror, a faster chirp time and faster signal processing, all of them described in detailed in [4].

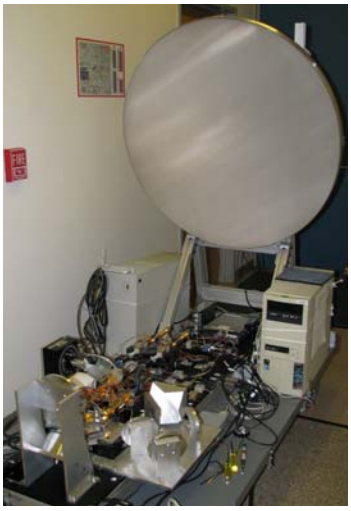


Fig. 1: Photograph of the optical system of the JPL's fast-scanning, long-range 0.67 THz imaging radar.

Further increasing the radar's imaging speed is important to avoid image blurring due to target motion during image acquisition, and it could enable larger fields of view to be obtained in a shorter time. Faster scanning optics will help reach somewhat higher speeds, but because a scanning motor's acceleration scales as the inverse square of the imaging time, it is unlikely to be done in a cost effective manner. As an alternative, the method described here doubles the radar frame rate without any modifications in the scanning mechanism, source power, or back-end electronics hardware. It is based on time-delay two-beam multiplexing, which was

previously described and demonstrated by us in the 4 m standoff radar prototype [5]. The multiplexing technique consists of generating a second beam with the power lost from the transmit/receive beam splitter (used to separate and combine the outgoing and incoming radar signals). The second beam goes through a quasi-optical waveguide to introduce a time delay with respect to the original beam. As a consequence, both signals can be distinguished from each other as a shift in the FMCW radar's down-converted frequency spectrum.

Originally, a waveguide approach to beam splitting was implemented, with a view toward a possible future extension to multiplexing a linear transceiver array. However, we found that discrete waveguide components used for duplexing and polarization rotation presented too-high ohmic losses and transmit/receive leakage. Therefore in [4], we proposed an alternative all-quasioptical approach to time-delay multiplexing, and its implementation is described here.

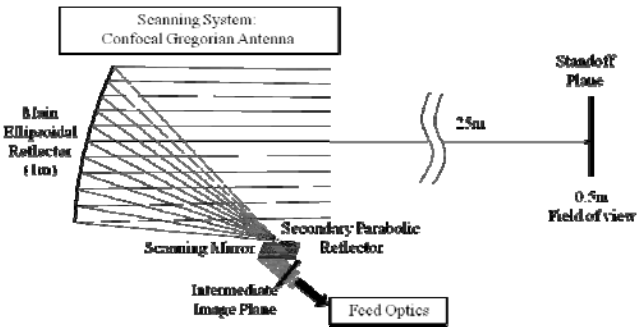


Fig. 2: Description of the scanning system.

Aside from improving a radar's imaging speed, the multiplexing technique can also be used to implement a fully coherent polarimetric radar transceiver with no additional transmitter or receiver hardware. In contrast, conventional polarimetric radars require dual transmitters and/or receivers dedicated for the two polarization components. The quasioptical multiplexing system describe here can easily be used for polarization measurements by just pointing the two multiplexed beams towards the same target point as described in next section. This polarimetric multiplexing could be useful in high frequency radar systems for future earth observation applications.

II. Quasi-optical System Description

The radar optical system can be divided into two main parts: the scanning system and the feed system. The scanning system is shown in Fig. 2. It is composed of the main ellipsoidal reflector with a far focus at the standoff plane 25 m away. The main reflector is illuminated by a secondary parabolic mirror that focuses a collimated beam to the main reflector's close focus. The collimated beam is generated at the feed optics, and it is scanned by a flat mirror mounted on orthogonal rotary motor stages. This mirror is rotated an angle θ_m about two axes (elevation and azimuth), steering the collimated beam by $\theta_{sm} = 2\theta_m$. Because of the confocal geometry, the beam is then focused at the standoff plane by the main antenna, and steered towards a stop in the field of view (FoV) situated at a distance from the FoV's center of $\rho_s \approx 2.5\theta_{sm}$, where θ_{sm} is given in radians (we have assumed a beam deviation factor of 1, for simplicity).

Such an optical configuration will scan the intermediate image plane's collimated beam towards different location ρ_s of the field of view. The feed optics used to generate the collimated beam consist of a simple parabolic reflector that transforms the horn beam into the collimated beam in the intermediate image plane. For the multiplexed system describe here, the feed optics is modified to implement spatial and temporal multiplexing of the beam as described in the following two subsections for the polarimetric and fast imaging implementation.

A. *Polarimetric Radar System*

The feed optics for a polarimetric measurement configuration is shown in Fig. 3. The first step is to divide the transmitted signal power into two beams using a beam splitter. The beam transmitted by the beam splitter, with horizontal polarization (referred in the following as H) is allowed to pass unaffected through a vertically oriented wire grid. Then it proceeds to the radar's scanning optics after reaching the feed parabolic reflector. This beam path is basically the same as without the multiplexing. The beam is collimated at the intermediate image plane and scanned along the field of view by the scanning optical system.

The other beam, reflected by the beam splitter, is first collimated and then passes through a second vertically oriented wire grid. Then it retro-reflects from rooftop reflector oriented at 45°, which rotates the beam's polarization from H to V. Therefore the beam now reflects from the second wire grid into the quasi-optical waveguide (i.e. free space reflectors). This series of reflectors have an intermediate focus placed at the same distance to the first wire grid, L_f, as transmit horn is. In this way, the two beams, now with orthogonal polarization, are co-aligned at the intermediate image plane. This implies that they are scanned to the same spot in the field of view by the scanning system; see Fig. 4. The quality of the beams is very good over the whole field of view.

The V beam is delayed in time by propagation through the quasioptical waveguide for a total extra path length $L_d \approx 100$ cm with respect to the unaffected H beam. This delay is key to discriminating between the two signals. From this delay, there will be a relative frequency shift of the V signal on the IF channel corresponding to a time delay $2L_d/c$, or equivalently, a range delay of L_d. As long as this length is much larger than the target object's range extent, there will be two distinguishable clusters of peaks in the FMCW radar's range

spectra. Figure 5 shows an example of such spectrum for the 670 GHz radar operating in a multiplexed polarimetric mode and illuminating a single target. The first cluster of peaks correspond to the H signal S_{HH}. The second cluster corresponds to the cross-polarization signal $S_{HV}+S_{VH}$, and it is located with a 50 cm range shift because the extra path length is only traveled through once for the case where polarization occurs. The final cluster of peaks, separated by the 100 cm range delay, corresponds to the S_{VV} polarization scattering parameter.

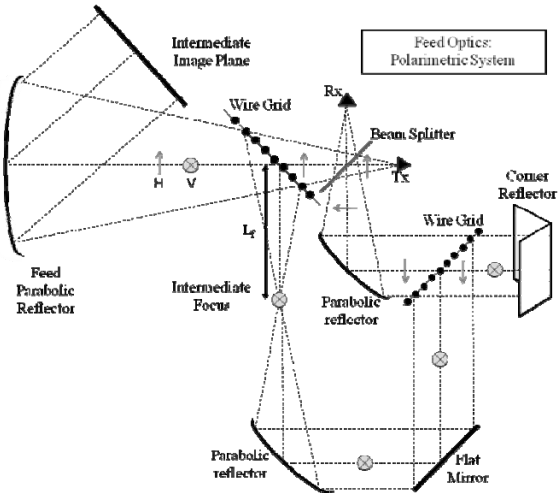


Fig. 3: Description of the feed system for the polarimetric system.

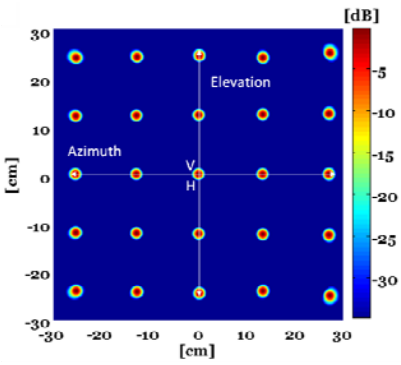


Fig. 4: Beams of the polarimetry radar system simulated with GRASP.

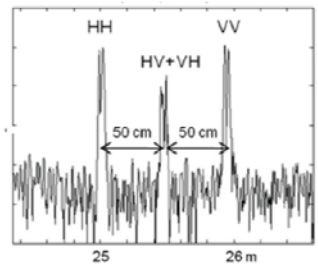


Fig. 5: Spectrum example of the radar system operating in a polarimetric detection mode.

B. *Fast Imaging Radar System*

The multiplexing technique was originally developed in [5] to reduce the acquisition time by a factor of two without the need of any additional RF hardware. This can be achieved in the current implementation by displacing the H and V beams so they point to different spots in the field of view. The field of view is divided in two halves, over which each beam scans separately. See Fig. 6. The division is done at the intermediate image plane level so both beams are then scanned together by the scanning system. As explained in [3], it is preferable in terms of speed improvement to divide the field of view horizontally when fast scanning is in the vertical direction. A division of the horizontal field of view by N will then be directly translated to an improvement of N in the acquisition frequency.

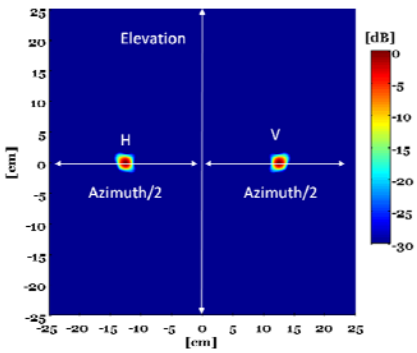


Fig. 6: Beams of the fast imaging radar system simulated with GRASP.

Figure 7 shows the scheme of the feed optics when configured for fast imaging operation. We want to have the beams pointing at ρ_s = ±FoV/4 in the horizontal plane. Therefore we need to introduce an angular beam tilt at the subreflector of the scanning optics of $\theta_{sm} \approx$ ±FoV/10. This beam tilt can be generated directly on the collimated beams at the intermediate image plane. This is done so both beams can be scanned simultaneously with the scanning antenna system. This beam tilt is represented in Fig. 7 as θ_h and it will be approximately FoV/10. The necessary beam tilt of the H beam can be achieved by displacing the transceiver a distance d_h over the focal plane (in such case $\theta_h \approx d_h$/F, being F the focal distance of the feed reflector). To achieve the -θ_h beam tilt of the V beam, we need to displace the intermediate focus of the quasi-optical waveguide so its equivalent focus (described with a gray triangle in Fig. 7) is at -d_h over the focal plane.

In this configuration. the H beam is also delayed in time with respect to the first one by the propagation through the quasioptical waveguide. Therefore, in the radar spectrum, both signals will be also separated by L_d. The beams point to different spots in the target, and the spectrum in this configuration does not have the cross-polarization signal S_{HV}.

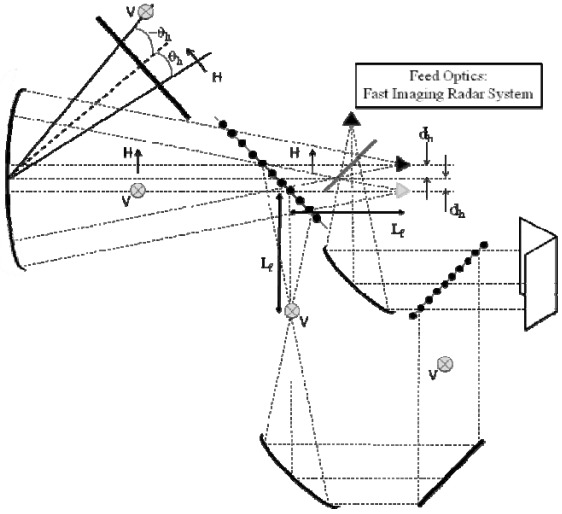


Fig. 7: Description of the feed system for the fast imaging configuration.

III. System Measurements

Figure 8 shows a photograph of the multiplexing implementation of the feed optics in our 675 GHz radar. The system has been validated in both configurations. The of use all-quasioptical components for duplexing (a beam splitter) and polarization rotation (a wire grid/rooftop reflector combination) ensures a low loss of 1-2 dB and negligible direct Tx/Rx signal leakage.

The beam profiles were experimentally validated by imaging small gold beads. Figure 9 shows the measured beam profiles at a similar spot over the field of view for the V and H signals. Looking to this figure, we can conclude that both signals present comparable resolution and similar level, validating the low loss propagation through the quasioptical waveguide.

Figure 10 shows an example of a fast 1 second image obtained with the multiplexing system. The image processing basically divides the scene in half and analyses the multiplexed signals spectrum for each half. Without the two-beam multiplexing, the image of Fig. 10 would have taken 2 seconds (0.5 Hz) to acquire.

IV. Concluding Remarks

The JPL's 670 GHz imaging radar is effective as a tool for performing a rapid long standoff imaging. The use of fast-optics and time-delay multiplexing has recently led to radar imaging frame rates of 1 Hz at 25 m standoff range. The system presented here is on the border of what can be achieved with commercial rotating mirrors and the limited available signal to noise related to high frequency components. Therefore future efforts will concentrate on multi-beam target illumination using a small transceiver array combined with a similar time-delay multiplexing system as the one presented here.

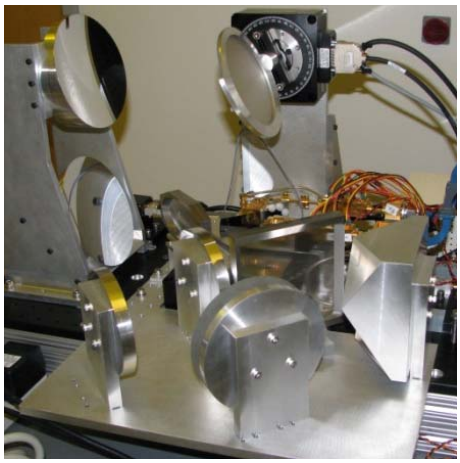
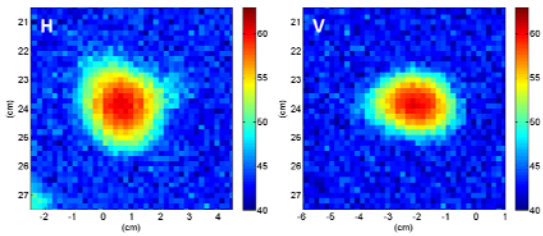


Fig. 8: Photograph of the multiplexing feed optics.



(a) (b)

Fig. 9: Multiplexed beam profile measurements: (a) horizontal and (b) vertical polarization.

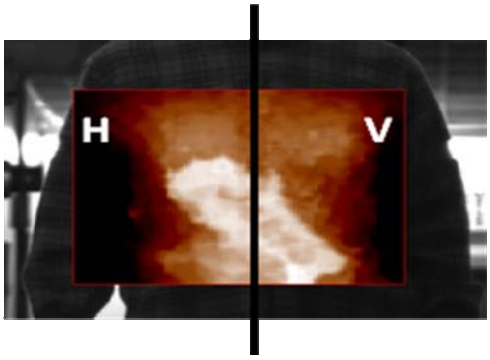


Fig. 10: Concealed object image with the fast configuration multiplexing.

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