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Signal Reduction due to Radome Contamination in Low-THz Automotive Radar

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***Abstract*—This paper investigates signal reduction due to contamination of low-THz radar radomes for outdoor applications. A measurement methodology is proposed to characterise the effect of different obscurants on electromagnetic wave propagation. This is achieved by measuring the ratio of two signals: one reflected from the reference target through the contaminated radome and another through the radome without the contaminant. The presence of water content in propagation media is the main cause of performance deterioration of sensors in rainy, snowy and foggy weather. Therefore, the reflectivity and transmissivity of water films on the radome has been measured and analysed at 150 and 300 GHz and measurement results are presented. The measured results are compared to a theoretical model and good agreement has been established. The results show strong correlation between signal reduction and uniform layer of water thickness.**

Keywords—Low-THz; Fresnel theory; reflection; transmition; water; automotive

I. Introduction

Low TeraHertz (low-THz) sensors operate in the frequency range of 0.1-1 THz occupying the region between the upper end of radio spectrum and the lower end of the Infra-Red spectrum. This frequency region is the least explored section of the electromagnetic spectrum due to the scarcity of commercial components [1-2]. However, recent significant progress in hardware developments for this frequency range opens up the opportunity to explore and study this range of frequencies. Low-THz radiation has found applications in different fields such as: biomedical science [3], security [4], material characterisation [5], automotive [6] and many others. Higher image resolution at low-THz frequencies can be achieved compared to microwave frequencies due to the potential wide operational bandwidth available in the THz bands. Additionally, THz radiation is less susceptible to blocking of signals by obstructions compared to optical sensors; for example, a single leaf will block the signal and blind the optical sensor, whereas at THz frequencies this will only introduce a few dBs attenuation. There is therefore a requirement for a thorough study to prove the feasibility of using THz frequencies for sensing in uncontrolled environmental conditions. The performance of THz sensors in the presence of different radome contaminants (mud, oil, grit, etc.) and various weather conditions (rain, snow, fog, etc.) requires investigation. The presence of water on the radome and in the atmosphere is one of the main reasons for the reduction in performance of outdoor THz sensors in adverse weather conditions. The reduction of signal in the presence of water in the propagation path is being studied in this paper.

The effect of water built up on the radome of the antenna, and the presence of water droplets in the atmosphere, on propagation characteristics has been a topic for research over the last few decades [7-11]. In [7], the propagation losses for varying precipitation rates have been measured over two years. The results are presented in two ways: the measured propagation losses in the rain with a wet radome and a dry radome. The propagation losses in rain with wet and dry radomes were compared and demonstrated a difference between 9 and 14 dB, respectively. The transmission losses through uniform layers of water [8] and water droplets [9] on radomes have been studied at microwave frequencies and considerable signal attenuation due to the "wetness" of the radome has been observed. The theoretical model of reflection and transmission of water films on the radome at 24, 76 and 140 GHz is presented in [10] and compared to the measurements at 76.5 GHz which show a loss of about 30 dB if the water layer is 1 mm thick. Attenuation in a uniform layer of water has been measured and compared with simulated data in the optical region and the results confirmed strong attenuation even with a very thin layer of water [11].

Lack of knowledge on signal degradation through a contaminated radome at low-THz frequencies was the motivation for this research which investigates the feasibility of low-THz sensors for outdoor applications. Signal reduction, due to the presence of the water film, in the propagation medium is strongly dependent on the signal frequency and the thickness of the water layer. A methodology is proposed to characterise transmission losses at two low-THz frequencies (150 and 300 GHz) when uniform layers of water is built up on the radome. Experimental results are discussed in this paper.

II. Methodology

The measurement methodology proposed in this paper is based on the direct implementation of the radar principle, i.e.

considering explicitly the ratio of the signal strength reflected from a reference target through the radome without obstruction to the signal received through a radome covered by contaminant at normal incidence.

The measurement setup is shown in Fig. 1. The monostatic radar consisting of collocated transmit and receive antennas is positioned vertically and is pointing upward. The transmit and receive signals are shown by P_i and P_R in Fig. 1 (a), respectively. A reference target with a known Radar Cross Section (RCS) has been suspended above the antennas. A Trihedral Corner Reflect (CR) has been chosen as a reference target with RCS of 29.4 dBsm. A sample of contaminant is placed between the antennas and the reference target in the path of the signal. This requires having a sample holder which is sufficiently rigid to provide a stable and robust platform that does not sag under the weight of the sample and is replaceable after each measurement. Other important characteristics for the sample holder are low reflection and low signal reduction which requires having a thickness equal to an integer of half wavelength and low refractive index. Closed cell polyurethane foam which has a thickness of 5 cm and a dielectric constant of approximately 1.2 at both operating frequencies has been chosen as a radome prototype and placed perpendicular to the direction of the propagation. Samples are placed on the sample holder in such a way to obscure the radar beam. The area that the sample needs to cover should be greater than the footprint of the illuminating beam, defined by the radiation pattern 3 dB roll-off, to guarantee that most of the energy passes through the sample. According to the distance between the sample holder and antennas (200 mm) and also the beamwidth of the antennas (azimuth and elevation angle of 10˚), the sample must cover an area exceeding a circle with an area of 55 mm^2. The advantage of this setup is that different samples can be introduced without requiring further alignment.

According to the reflection and transmission coefficients from Fresnel theory [12], the complex refractive index of a material, $\tilde{n}(f,T)=n-jk$, which depends on both frequency and temperature, will result in reflections of some of the energy at the boundaries where the refractive indices of two media are different. Some of the incident power (P_i) is reflected back to the antenna at the first interface and is shown by P_r in Fig. 1(a). The rest of the energy will propagate through the sample. The reflection and transmission coefficients of each sample are different and are based on the permittivity, thickness and shape of the sample. The signal reduction that occurs due to the presence of the sample is combination of various phenomena such as: reflection, refraction, absorption and scattering and labelled as *"Transmissivity"*, and can be calculated by:

$$T(dB)=10\log\left(\frac{P_t(t)}{P_t(t_0)}\right)-10\log\left(\frac{P_R(t)}{P_R(t_0)}\right) \tag{1}$$

$P_t(t)$ is the transmitted power through the radome when is covered by the sample, which is P_i-P_r, and $P_t(t_0)$ is the transmitted power through the radome of the reference signal without a sample, where $P_t(t_0)$ almost equals P_i as there is negligible reflection from the sample holder. $P_R(t)$ and $P_R(t_0)$ are the reflected powers from the reference target through the radome covered by a sample and through the radome without a sample (reference signal), respectively.

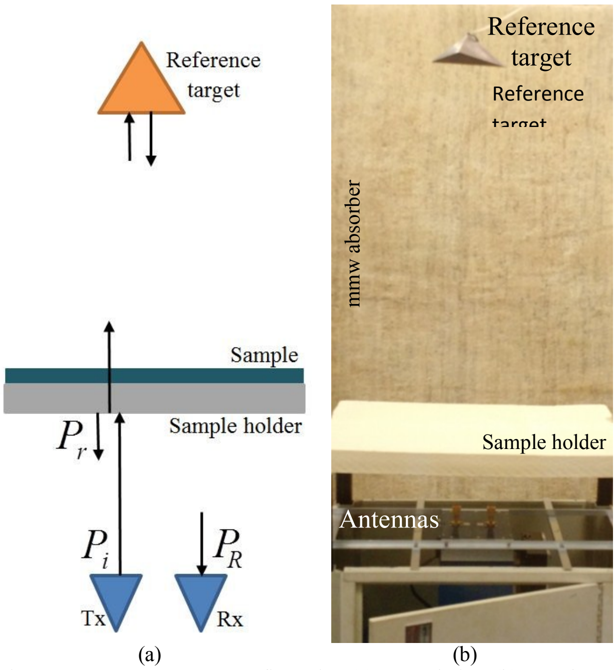

Fig. 1. Measurement setup configuration (a) general view (b) actual setup

III. Measurement

The measurements were conducted using two radar systems: a Frequency Modulated Continuous Wave (FMCW) radar with a sweep frequency of 144 to 150 GHz and a Stepped Frequency Radar (SFR) with the sweep frequency of 282-298 GHz. The SFR is a system based on an Agilent FieldFox portable Vector Network Analyser (VNA) with VivaTech [13] up- and down-converters. The RF input of the up-converter spans a frequency of 2-18 GHz and the corresponding frequency of the RF input of the down-converter is 282-298 GHz.

As mentioned earlier, this paper concentrates on investigating the transmission loss of uniform layers of water. The transmissivity due to the presence of the water is factor of frequency, thickness and formation of water on the radome. One of the challenges in this measurement is to provide thin uniform layer of water (due to the adhesion and surface tension properties of water). To do that, tissue paper soaked with water has been placed on the radome. A known amount of water is deposited on a tissue paper with area of 235 mm^2 enabling the thickness of water to be calculated using the equation for the volume of a cylinder. In order to produce a defined thicker layer of water several tissue papers are stacked together. This technique gives ability to provide uniform layer of water and an accuracy of producing a water layer thickness of 0.05 mm. Possible errors in this measurement setup could arise from any air gaps between the tissue papers and non-uniform density of paper itself.

The received signal is recorded in the frequency domain and transformed to the time domain using an Inverse Fast Fourier Transform (IFFT). The signal in the time domain gives the ability to distinguish the reflection from different interfaces.

Therefore, the received signal contains leakage between the transmit and receive antennas, direct sample reflection and the reflected signal from the target transmitted through the radome, each occurring at a corresponding propagation delay. Two set of measurements are required, namely (i) a reference measurement and (ii) a water measurement. The reference signal has been measured from the reflection of the reference target (CR) without any contamination (water) on the radome. Fig. 2 illustrates the reference signal and the wave transmitted through the radome which is covered by 0.2 mm of pure water (deionized) at 300 GHz, as an example.

The measured reflectivity and transmissivity of pure water film with respect to the thickness of the water at both frequencies are represented in Fig. 3 and Fig. 4, respectively. The measurement points shown with marker points (stars for 150 GHz and diamonds for 300 GHz) are the results after averaging over 10 measurement points. The least squares fit lines for 150 and 300 GHz are shown respectively as the dashed and solid lines. Generally, transmission through pure water decreases rapidly as the thickness of the water film increases. The transmissivity of pure water at 300 GHz decreases more rapidly than at 150 GHz. The transmissivity of water was measured up to a water layer thickness of 0.45 mm, as above that the received signal from the target was in the measurement noise floor. However, the result at 150 GHz is shown up to a 0.6mm, because the noise floor of the 150 GHz equipment is lower and also the transmissivity at this frequency is higher. Water layer reflection and transmission has a non-trivial trend, as the refractive index of water is a complex value. The imaginary part of the refractive index gives rise to attenuation inside the water. Characterisation of the reflection and transmission of the water layer is required as a part of longer-term automotive low-THz radar research programme. Similar characterisation of the transmissivity of various materials with different moisture level will be considered in future work.

Our study uses a theoretical model which is based on the Fresnel theory [12] of reflection and transmission for multilayer structures. The model is developed for a four layer structure: air-radome-water-air. The reflection coefficient in the first medium (air) and the transmission coefficient in the fourth medium (air) are calculated by:

$$R_1 = \frac{\eta_{in} - \eta_1}{\eta_{in} + \eta_1} \tag{2}$$

$$T_4 = \frac{2\eta_{in}}{\eta_{in} + \eta_1} \tag{3}$$

where η_{in} is the input impedance at the first interface and η_1 is the wave impedance of the first medium (air). The calculated and measured reflectivity and transmissivity of pure water at both frequencies are plotted in Fig. 5 and 6 which show excellent agreement between the calculated and measured results. The small discrepancy is due to many factors as mentioned earlier; such as presence of air gap, non-uniformity of water layer, as well as evaporating water which will change the thickness of water. However, the results yield good

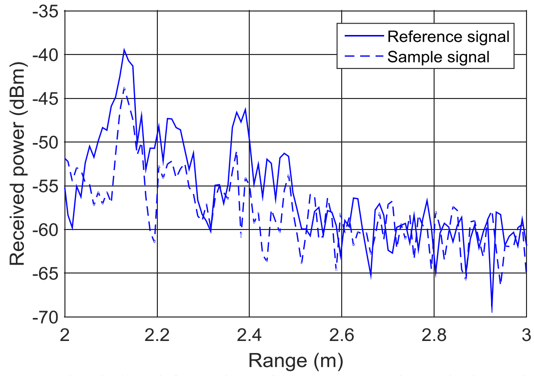

Fig. 2. Received signal from the reference target through the radome without water (reference) and through the sample (0.2 mm of pure water) at 300 GHz

agreement between the modelling and measurement techniques.

Reflection from pure water (Fig. 5(a) and 6(a)) increases and it reaches its maximum for a relatively thin layer of water which depends on the wavelength of the signal, and then it stays constant. The reflection of pure water is at its maximum of-3.3 dB with the thickness of 0.15mm at 150 GHz and -4.6 dB for 0.1 mm thickness at 300 GHz. Fig. 5(b) and 6(b) illustrate that signal reduction in 0.5 mm and 0.45 mm water layers for 150 and 300 GHz reaches about 20 dB, respectively. It is worth mentioning that, a water layer of uniform thickness does not form on the radome in a real-life scenario. The build-up of water on the radome in outdoor applications typically leads to randomly distributed water droplets. Characterisation of the transmissivity through layer of water droplets on the radome is addressed in a future publication.

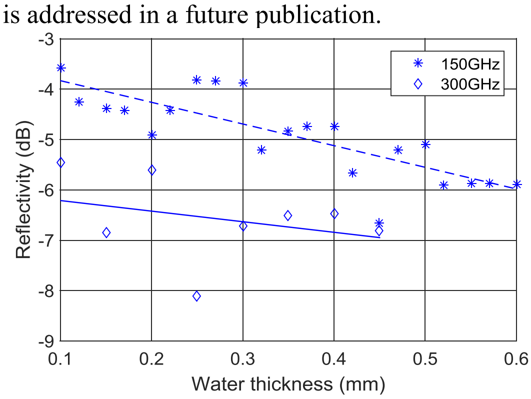

Fig. 3. Reflectivity of pure water film at 150GHz and 300 GHz

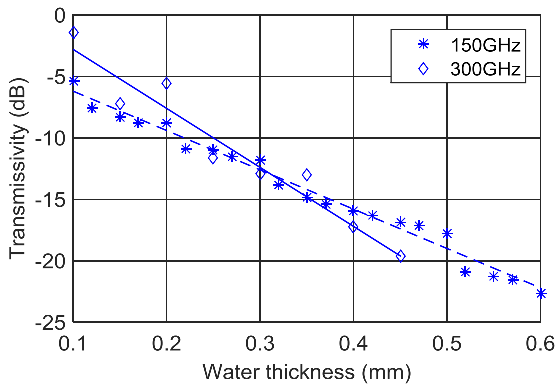

Fig. 4. Transmissivity through pure water film at 150 and 300 GHz

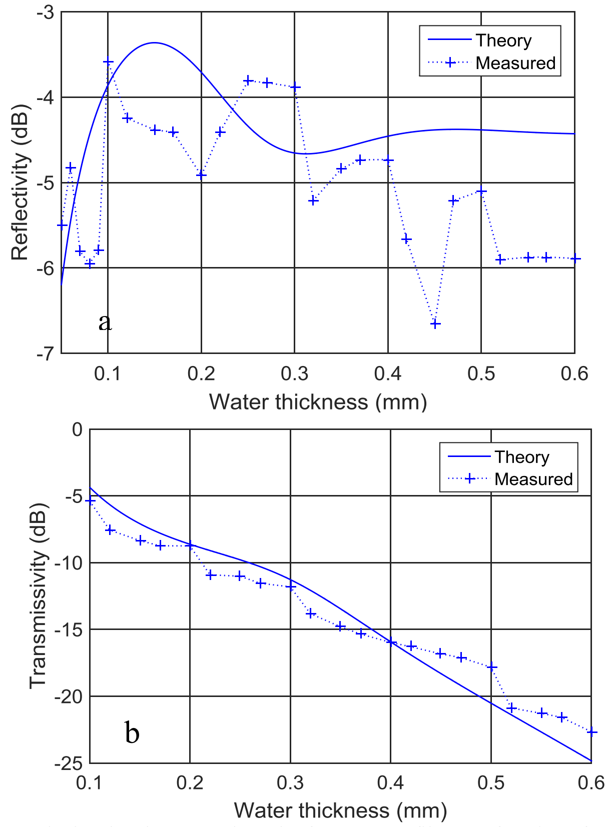

Fig. 5. Calculated and measured result of pure water film as a function of water thickness at 150 GHz at 23˚ (a) reflectivity (b) transmissivity

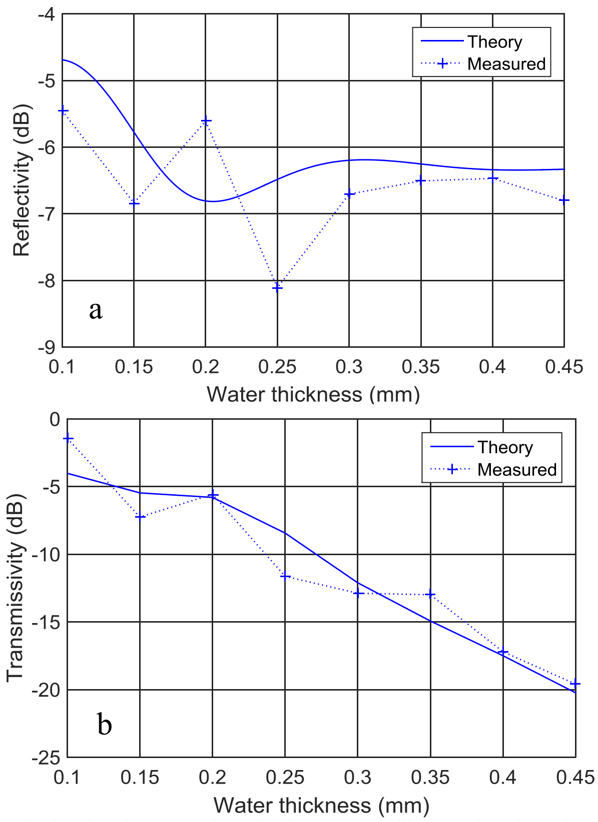

Fig. 6. Calculated and measured result of pure water film as a function of water thickness at 300 GHz at 23˚ (a) reflectivity (b) transmissivity

IV. Conclusion

The measurement methodology and results for reflectivity and transmissivity of a uniform water layer of various thicknesses at 150 and 300 GHz are presented in this paper. The measured results are found to be in very good agreements with the theoretical model and which describes signal reduction in the presence of layers of water on a radome. Proper design of radomes to minimise the adhesion of water on the radome is a topic which needs to be considered for outdoor applications of low-THz technologies. However, taking into account that formation of the uniform layer of water is an unlikely event and instead distributed water droplets will be more likely to present on a radome. Water droplets may lead to less severe signal reduction and therefore, investigation of the transmissivity through a layer of water droplets is the topic of future study including the effects of the presence of contaminated water.

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