Comparison of Diffuse Roughness Scattering from Material Reflections at 500-750 GHz

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Abstract—In this paper, an ultra-wideband Terahertz (THz) channel measurement campaign in the 500-750 GHz frequency band is presented. Power levels received from signal transmission by reflections off 14 different materials were measured in an indoor environment at Non-Line-of-Sight (NLoS) between the Transmitter (Tx) and Receiver (Rx), and compared to power levels received at Line-of-Sight (LoS) transmission. Frequency up-converters were used to transmit the signal using 26 dBi horn antennas at the Tx and Rx side and the signal was measured using a Vector Network Analyzer (VNA). From the data collected, the signal losses due to absorption and diffuse scattering from the rough surface of each Material Under Test (MUT) are calculated. The power delay profile (PDP) is presented, where multipath clustering due to diffuse scattering is observed for materials which have a high frequency selectivity, while less scattering and mostly specular reflection is shown for materials with low frequency selectivity.

Index Terms—Diffuse Scattering, Multipath, Power Delay Profile, Reflection Loss, Terahertz (THz).

I. INTRODUCTION

As the need for higher data rate communications and greater spectrum availability is becoming more apparent over the years [1], the research community has been motivated to explore what has been described as the last piece of RF (radio-frequency) spectrum puzzle, known as the Terahertz (THz) band (0.1-10 THz) [2]. Spectrum allocation as yet has been limited to frequencies up to 300 GHz for applications (THz) band (0.1-10 THz) [2]. Spectrum allocation as yet has been limited to frequencies up to 300 GHz for applications related to cellular communications, military and radar [3]. As the spectrum is mostly unoccupied and unregulated above these frequencies, it is important to define how this part of the spectrum can be used to satisfy the ever-increasing need for capacity and high speed communications. Since the THz wave can only propagate over a short distance, applications that have been identified in the THz band include Kiosk downloads, short range Local Area Networks (LAN’s) as well as data propagation within desktops and around a payload on board a satellite [4]- [7].

Exploitation of the spectrum in the lower end of the THz spectrum (0.3-3 THz) is very promising since the atmospheric attenuation at these frequencies is not very high and atmospheric windows exist that allow for data propagation over short distances [8]. Furthermore, at these frequencies, the first electronic circuits have been developed due to recent advances in the semiconductor technology that allow for signal generation with sufficient power levels. At these high frequencies, the attenuation experienced by the propagating wave due to atmospheric conditions becomes severe as the distance increases. Since the signal propagation is of a very short wavelength and the applications identified are within environments with many reflectors, it is very important to understand how interaction with materials of different thicknesses and roughness levels affects the signal propagating.

Measurements for reflection and penetration losses have been conducted at millimeter-Wave (mmWave) bands [9]-[12]. In [9] reflection coefficients and penetration losses for measurements conducted at 28 GHz using outdoor buildings are presented. Measurement results show that outdoor building walls are excellent reflectors while a relationship has been found between the penetration loss and distance of the propagating signal. These measurements included materials such as glass, brick, concrete and drywall. Moreover, penetration loss studies have also been extended to the THz band [13]-[15]. In [16] THz measurements have been carried out at carrier frequencies of 100, 200, 300 and 400 GHz at Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) off building walls. The Bit Error Rate (BER) performance is measured in relation to the transmitted power. It is found that the effect of scattering from the rough surface of the wall is much smaller than the effect of absorption at all measured carrier frequencies, while the absorption losses show an increasing trend as the frequency increases.

This work presents measurements for signal losses due to absorption and rough surface scattering by interaction with different materials in an indoor environment with 250 GHz bandwidth averaged over 1600 samples by the VNA. The setup consists of a Transmitter (Tx) and Receiver (Rx) arranged in a LoS and NLoS configuration (specular reflection) from which we obtain the S-parameters. The power received in the LoS scenario is compared to that received in the NLoS scenario via reflections off the MUT from which we compute the associated losses. The data is further analysed by presenting the Power Delay Profile (PDP) and considering the effects of clustering due to multipath propagation from the rough surface of different material.
II. MEASUREMENT SETUP & CALIBRATION

The objective of the measurement campaign is to compute the signal loss of the MUTs in the 500-750 GHz frequency band by utilizing S-parameter measurements. Two different measurement setups were deployed at the UK’s National Physical Laboratory (NPL) to perform the measurements. In the first setup, as shown in Fig. 1(a), the S-parameters in free space between a nominally identical pair of transmit-receive WM-380 waveguide horn antennas with no MUT present in between the antenna pair was measured. The measurements were carried out in a LoS configuration. In the second setup, as shown in Fig. 1(b), the S-parameters were measured with the transmit-receive antenna pair in NLoS configuration and various MUT placed interchangeably in the propagation direction at an oblique angle of 45° with respect to the antenna pair. The S-parameter measurements from both the LoS and NLoS configuration were later processed to calculate the losses associated with the MUT.

The S-parameter measurements were performed using a Keysight Technologies PNA-X Vector Network Analyzer (VNA) configured with two Virginia Diodes Inc (VDI) extender heads fitted with WM-380 [17] waveguide test ports and two nominally identical VDI WM-380 diagonal, vertically polarized horn antennas one for each of the extender heads. These extender heads operate from 500 GHz to 750 GHz. The VNA with the extender heads combination was calibrated using a Short, Offset-short, Load and Thru (SOLT) technique using standards from a WR 1.5 calibration kit. The short, offset-short and load are one-port devices that are used as reflection standards. The standards correct for errors in the measurements due to system directivity, source mismatch and reflection tracking. The thru connection is effectively a null two-port device and is used, along with the reflection standards, to correct for errors in the transmission measurements (e.g. load match, transmission tracking and, if necessary, any crosstalk errors) [18]. The performance of these standards has been verified previously against UK primary national reference standards thus, establishing metrological traceability to the international system of units (SI) for these measurements [19]. The extender heads have a measured dynamic range of better than 80 dB (for an IF bandwidth of 10 Hz) and a test port power of typically -25 dBm [20].

Following the calibration, a pair of VDI WM-380 diagonal horn antennas were attached to the calibrated waveguide reference planes of the extender heads and both the extender heads along with the diagonal horn antennas were positioned facing each other in LoS mode with a separation of approximately 23 cm for the measurements. The extender heads were attached to optical posts of height 150 mm which are sufficiently high to minimize any unwanted ground reflection of the propagated signal from the horn antennas. The height of the optical post is optimized depending on the separation distance between the horn and the half power beam width of the horn antenna. At these frequencies, the measured S-parameters between the horn antennas are very sensitive to positional inaccuracies. Hence x- and y-axis manual translation stages with 10 µm accuracy [21] and 360° rotation positioners [22] were used for each extender head to ensure good LoS alignment between the boresight of the two horn antennas by maximizing the measured $S_{21}$. For the NLoS measurements, the material under test (MUT) was mounted in a sample holder at an oblique angle with respect to the antennas. The rotational positioners were used to set a precise 45° angle between the horn antenna boresight and the MUT plane and the manual translation stages were used to set precise distance separation between the horn antenna and the MUT.

Initially, the $S_{21}$ was measured between the Tx-Rx antenna pair for different azimuth angle by rotating the receive horn antenna in the azimuthal plane using a precise rotational positioner and keeping the position of the transmit horn antenna fixed. This is plotted in Fig. 2 which shows an approximated radiation pattern at the band edge frequencies, the centre frequency and 557 GHz. 557 GHz is an important frequency due to the high level of attenuation at this frequency, in addition to 750 GHz, due to the molecular absorption of water vapour as observed in our previous work [23]. A careful analysis of Fig. 2 shows that $S_{21}$ is the lowest at 557 GHz, as expected, due to the strong atmospheric attenuation – i.e. the attenuation is more than 6 dB higher.
than the attenuation at 625 GHz. The measured 3 dB beamwidth at 625 GHz is approximately 5.5°. The uncertainties associated with the measurements in Fig. 2 are expected to be higher relative to similar measurements made in an anechoic chamber environment due to the uncontrolled reflections from the multipath environment. The results in Fig. 2 therefore provide an approximate indication suitable for understanding the channel attenuation and the radiation behaviour of the antenna and for determining the suitability of the specific horn antenna for the frequency band of operation.

### III. RESULTS & ANALYSIS

To calculate the losses from reflections off the MUT, we compare the power received in the LoS free space measurement with that of the NLoS reflection measurement with the different MUTs. The signal losses are computed using equation (1) where $P_{r,\text{LoS}}$ is the received power obtained under LoS conditions in Fig. 1(a) and $P_{r,\text{NLoS}}$ is the received power under NLoS conditions in Fig. 1(b). In this way, the free-space-path-loss is canceled out and only the losses as a result of absorption from the material and scattering are present. The dimensions and thickness of each MUT is shown in Table I.

$$L[\text{dB}] = P_{r,\text{LoS}} - P_{r,\text{NLoS}}$$ (1)

The losses resulting from interactions with the MUT can be seen in Fig. 3. Firstly, in the first set of measurements, metal is tested in the form of aluminium, brass, and copper which are considered as perfect reflectors. In Fig. 3(a) we can see the loss due to reflection from aluminium. The losses for brass and copper are almost identical and are omitted from the plot. As expected the loss due to absorption is very small and very close to the theoretical loss of 0 dB. Due to minor errors in symmetrical placement of the antennas with respect to the MUT and measurements of the separation distance, the loss is not exactly 0 dB and is slightly higher (i.e. around 3 dB), without any notable fluctuations. Rohacell of two different thicknesses was also tested as a material considered as foam which has a low dielectric constant close to that of air and should theoretically have a high absorption loss. The results show that losses in excess of 30 dB were calculated across the entire frequency range. Moreover, the high frequency
selectivity of Rohacell and low permittivity indicate that this is an in-homogeneous material that behaves as multi-layer medium (rohacell + air) which could cause reflections within the material itself. The thickness of the rohacell samples also seems to have an effect on the frequency selectivity as for the thin sample 5 peaks are observed while for the thicker sample 2 peaks are observed that are much wider and appear at different frequencies. Similar behavior can also be observed from reflections off grey foam with high losses above 25 dB and high frequency selectivity. Furthermore, common material found in buildings such as concrete, plasterboard and hardboard are also tested. Signal loss from concrete is very small with an average loss of around 7 dB while hardboard and plasterboard shown slightly higher losses of around 12 dB and 12-16 dB, respectively. Plasterboard is also slightly frequency selective whereas the other materials exhibit more specular reflection.

The second set of measurements are shown in Fig. 3(b). Glass has a stable loss of around 7 dB and MDF has a loss varying from 15-20 dB, showing an increase as the frequency increases. No fluctuations in losses are observed for both materials. Polyester showed losses ranging between 6 and 8 dB throughout most of the range, except between 550 and 680 GHz where a peak appears, reaching almost 40 dB. Plywood show losses varying between 13-22 dB while for acrylic the losses observed vary between 10-15 dB with consistent fluctuations that gradually decrease as frequency increases. Lastly, We would expect the same absorption loss to exist in both LoS and NLoS setups, therefore, when taking the difference of the losses, we find that the 557 GHz loss is almost entirely canceled out. The moisture in the air would have changed a bit between the two measurements and therefore a small difference may appear at 557 GHz.

To further extend the propagation analysis, the PDP which is a plot of relative received power as a function of excess delay, with respect to a fixed time delay reference, is computed via Inverse Fast Fourier Transform (IFFT) of the received signal. Fig. 4 shows the reflection measurement setup for Aluminium (a), Concrete (b) and Rohacell (c). Fig. 5 shows the PDP resulting from the measurements of Aluminium (a), Concrete (b) and Rohacell (c). The peaks observed for all three materials is that of LoS propagation which is the main delay component, arriving with a 0.776 ns delay. The Free Space Path Loss (FSPL) corresponding to the delay line found, can be calculated using equation (2) and is derived from the Friis free space transmission formula. Where, $c$ is the speed of light, $f$ is the centre frequency, $d$ is the distance the multipath components will travel, $G_t$ and $G_r$ are the Tx and Rx antenna gains. The calculated FSPL for the LoS component is calculated to be around 23.6 dB with centre frequency at 625 GHz.

$$\text{FSPL} = 20\log_{10}(d, f) + 20\log_{10}\left(\frac{4\pi}{c}\right) - G_t - G_r \quad (2)$$

In order to inspect the effects of surface roughness of the MUT a closer look is needed into the LoS peak, to identify whether clusters of multipath components are present. The largest kind of delays we would expect to see from reflections scattered off the material itself are not going to be delayed any more than 10 mm, which corresponds to 0.03 ns. With the bandwidth used, we have 0.004 ns delay bins so it is possible we could see such delay taps. We therefore need to look at the data close to the peak within 0.1 ns to see what clusters there are. In case of Aluminium (a) and Concrete (b), no clusters can be observed close to the LoS peak which is well defined and the reflections are considered mostly specular. For Rohacell (c), we can observe 4 different clusters close to the peak which cause it to widen and become more distorted. This effect is due to the high frequency selectivity of the material indicating that the surface can be considered rather rough in comparison to aluminium and concrete. The same effects would be expected also for other materials which are also highly frequency selective.

**IV. CONCLUSION**

Absorption and surface roughness losses were measured and presented in the 500-750 GHz band for 14 different materials. Minimal losses were found for metals showing that the effect of roughness is minimal and therefore the reflections are considered mostly as specular. Concrete has proven to be a good reflector with small losses varying up to
5 dB. Losses for plasterboard, hardboard and MDF indicate that energy has been lost due to penetration while polyester and polycarbonate are frequency selective and clusters were observed. Materials considered as foam such as rohacell are highly frequency selective and clusters of multipaths were also observed due to diffuse scattering from its rough surface. Limitations of this study include the lack of measurement data that do not allow for accurate characterization of the materials in terms of scattering behaviour based on the thickness of the material and angle of incidence/reflection in the angular domain. Lastly, as the propagation distance is very short, possible applications in this band are intra-device communications, propagation on-board a desktop and around a satellite payload.

REFERENCES