Ultra Wideband Material Characterization for Indoor Propagation

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Abstract

The information on electromagnetic properties of building materials in the ultra wideband (UWB) frequency range provides valuable insights in assessing the capabilities and limitations of UWB technology. This research examines propagation through typical construction materials and their ultra wideband characterization. Ten commonly used construction materials are chosen for this investigation. Results for the insertion loss and the dielectric constant of each material over a frequency range of 0.5 to 15 GHz are presented.

I. Introduction

At a fundamental level, the propagation of UWB signals, as for any electromagnetic wave, is governed, among others, by the properties of materials in the propagation medium. The information on electromagnetic properties of building materials in the UWB frequency range provides valuable insights in appreciating the capabilities and limitations of UWB technology for indoor and indoor-outdoor applications. Some results on ultra wideband characterization of building materials have been reported during the past decade. Hashemi has presented an excellent review and comparison of published results for different indoor penetration losses in the UWB frequency range [1]. However, these results are often inconsistent, making the assessment of indoor UWB propagation effects unreliable. For example, in [1] significantly different measured values of 7 dB, 8.5-10 dB, and 13 dB for the insertion loss of concrete blocks are cited.

The aim of paper is to perform ultra wideband characterization of typical building materials. The delay and loss of each material and their variations versus frequency are presented. The results of this investigation provide valuable insights into the transient behavior of a pulse as it propagates through construction materials and structures. Ten commonly used construction materials are chosen for this investigation. These materials include wallboard, cloth office partition, structure wood, wooden door, plywood, glass, styrofoam, brick wall, concrete blocks, and reinforced concrete pillar. Radiated measurements are used in this work as they lend themselves to non-destructive and broadband applications. Results for the insertion loss and the dielectric constant of each material over a frequency range of 0.5 to 15 GHz are presented.

II. Measurement Procedures

The complex dielectric constant of the material that constituters the propagation medium, is evaluated through the measurement of an 'insertion transfer function', defined as the ratio of two frequency-domain signals measured in the presence and in the absence of the material under test. The measurements may be performed in either the time domain using short duration pulses, or in the frequency domain using sinusoidal signals. The transmitter and receiver antennas are kept at fixed locations and aligned for maximum reception. The material to be measured is placed at nearly the mid-point between the two antennas. The distance between the antennas should be sufficiently large so that the material is in the far

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field of each antenna. With this arrangement, the electromagnetic field incident on the material is essentially a plane wave. The material under test is assumed to be in the form of a slab with thickness *d* and held in position such that the plane wave is normally incident on the slab. After the measurement system is prepared, initially the reference signal $V^{fs}(j\omega)$ is measured in the absence of the material. Then, the signal $V(j\omega)$ is measured with the material layer in place. The insertion transfer function is obtained as

$$H(j\omega)=\frac{V(j\omega)}{V^{fs}(j\omega)} \tag{1}$$

When measurements are performed in the time domain, fast Fourier transform is used to convert the signals from the time-domain to the frequency domain and then the insertion transfer function is calculated. Care must be taken to ensure that conditions set during the free-space measurement are as closely identical as possible to those for the measurement carried out with the material slab. It is difficult to perform *in-situ* and free-space measurements with identical conditions. To overcome this challenge, walls were built on moving carts to obtain exact free-space reference measurements. To ensure better accuracy in characterization of materials, six different measurements are performed for each material. These include four time-domain measurements, with two different pairs of antennas and two pulse generators with different pulse waveforms, and two frequency-domain measurements using two pairs of antennas. The presented data are the averages of these six measurements. In each measurement, two wideband TEM horn antennas are used as transmitter and receiver. Measurements are performed both in the time domain using less than 100ps pulses along and a sampling oscilloscope, and in the frequency domain over a frequency range of 0.5 to 15 GHz using a vector network analyzer.

III. Signal Processing and Analysis Techniques

Frequency-domain measurements are performed in a frequency range from 500 MHz to 15 GHz. Over a given frequency range, 801 complex (magnitude and phase) data points, which are the maximum number of points allowed by the vector network analyzer, can be collected. This limitation on the number of points imposes a limit on the measurement resolution. A low-pass finite-impulse-response (FIR) filter is used to remove the noise beyond the antenna bandwidth. The cutoff frequencies of the filter are adjusted to remove noisy regions. For time-domain measurements, 128 traces are averaged and acquired in a 5 ps sampling time using a sampling oscilloscope. Offset adjustment is achieved through load calibration and post-processing. The window in which the signal is acquired spans more than 10 ns and consists of 2048 points.

Time gating is used to reduce significantly the undesired effects such as reflections from the surrounding walls and scattering from edges. For time gating to be efficiently implemented, three conditions have to be met. First, the transmitter and the receiver antennas should be positioned away from the reflecting surfaces. Second, samples should have relatively large surface dimensions in order to minimize the edge effects. Finally, there should be flexibility in adjusting the distance between the antenna and the sample. Time gating can also be used to isolate a desired portion of the received signal; namely, the first single-pass of the signal transmitted through the slab. In this application, the sample thickness should be large enough to yield sufficient delay. Thus, not only zooming on and extracting the first pulse, but also removing all delayed pulses due to multiple reflections inside the slab become possible.

The insertion transfer function $H(j\omega)$ is related to the complex dielectric constant $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ through the following expression

$$\left(x + \frac{1}{x}\right)\sinh(xP) + 2\cosh(xP) - \frac{2}{S_{21}} = 0\,, \qquad (2)$$

where $x = \sqrt{\varepsilon_r}$, $S_{21}(j\omega) = H(j\omega)e^{-j\omega\tau_0}$, $\tau_0 = d/c$, and $P = j\beta_0 d$. This equation can be solved numerically using two-dimensional search algorithms.

IV. Measurement Results

Ten different wall material samples commonly encountered in building environments are selected for UWB characterization. These materials and their wall thickness are: wallboard (1.16992 cm), cloth office partition (5.9309 cm), structure wood (2.06781 cm), wooden door (4.44754 cm), plywood (1.52146 cm), glass (0.235661 cm), styrofoam (9.90702 cm), brick wall (8.71474 cm) concrete block wall (19.45 cm), and reinforced concrete pillar (60.96 cm). The distance between the sample and the antenna should be long enough to ensure that the sample is in the far field of the antenna. Most of our measurements were performed with a total distance of 1-3 meters. An experiment was performed by varying the distance between the antennas and the sample in steps of 0.25m. No significant changes in results, other than in signal levels, were observed.

A straight line is used to model the insertion loss versus frequency. The fitted insertion transfer functions (loss) and dielectric constant for different materials are shown in Figures 1 and 2, respectively. The cloth partition sample shows higher loss due to support elements inside the partitions. The results for brick wall and concrete block wall are presented over smaller bandwidths because of higher losses of these materials that reduce their bandwidths. The dependence of dielectric constant on frequency can be modeled as a straight line with a very small negative slope. However, the dielectric constant for the brick has a small positive slope that is believed to be due to the inhomogeneous nature of the sample. The dielectric constant of the glass sample could be measured by neither the time delay between peaks of the received pulses nor the single-pass technique. This is due to the relatively small thickness of the glass sample used in the measurement. The reinforced concrete wall resulted in a very small amount of received power. No further processing could be performed, but an average dielectric constant was obtained by measuring the time delay between incident and received pulses.

V. Conclusion

Ultra wideband characterization of materials and walls commonly encountered in indoor wireless environments has been carried out. Measurements were carried out in both time domain and frequency domain. Results from different techniques agree well, thus ensuring the reliability and accuracy of the measurements. Ten different materials were tested and results were presented in terms of insertion transfer function (loss) and dielectric constant. The presented results should serve as a basis for further studies in developing appropriate models for UWB channels. The results are also very useful in UWB link budget analysis.

References

1. H. Hashemi, "The Indoor Radio Propagation Channel," IEEE Proceeding, vol. 81, pp 943-968, 1993.

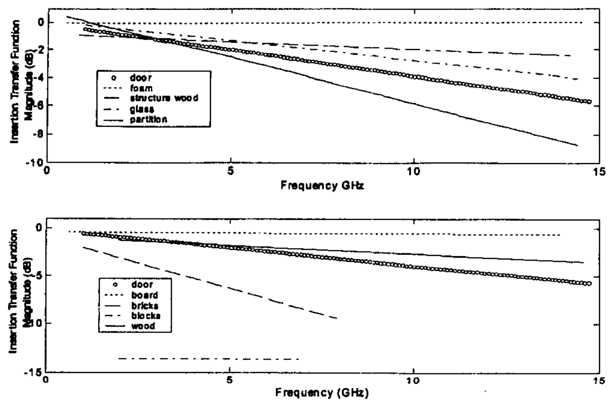

Figure 1. Insertion transfer function (loss) versus frequency for building materials tested.

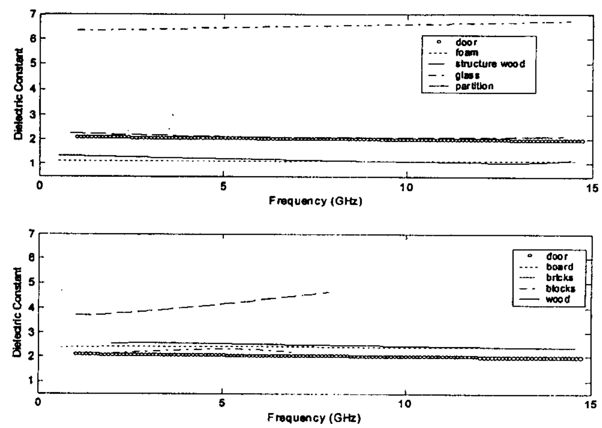

Figure 2. Dielectric constant versus frequency for building materials tested.