An electromagnetic model for detecting explosives under obscuring layers

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Abstract

Recently, there has been increasing interest in object imaging and detection behind obscuring layers because of applications in detection of improvised explosive devices (IEDs) and suspicious materials. Millimeter (MMW) and terahertz waves show promise in detecting and imaging objects through clothing or packaging materials. In this paper, we discuss an electromagnetic model based on a multi-layer medium which may represent hidden explosives underneath clothing on a person. The dielectric model of the material of interest has been studied. Simulations of the wave propagation through this multi-layer medium model are performed, and the results show indications that MMW and terahertz waves can be used in detection and imaging of suspicious objects underneath normal clothing, which leads to possible detection of IEDs.

Introduction

Millimeter (MMW) and terahertz wave propagation and imaging through obscuring layers are topics of recent interest with practical applications in security, inspection, and surveillance. Both millimeter and terahertz waves show promise in detecting and imaging objects under obscuring material. One important and practical scenario consists of hidden explosives underneath normal clothing in a standoff position. An electromagnetic model for this scenario is necessary, including the dielectric modeling of materials. We present an electromagnetic model based on multi-layer media, where multiple reflections within each layer are included. It has the flexibility for more complicated structures to be added, including rough surface interfaces and small inclusions in layers, which were used in our previous study on sea-ice remote sensing [1]. The model can also be used to calculate the angular correlation of two waves at two observed angles. Simulations of wave pulses propagated through this multi-layer structure are presented. This model provides a tool for estimating the response at different frequencies and configurations which is instrumental for modeling the imaging and detection of objects.

An electromagnetic multi-layer model

The multi-layer model is shown schematically in Fig. 1. This model represents electromagnetic wave propagation through clothing and human skin in a standoff position. Configuration A is where there is a plastic explosive composite present, while configuration B is where there is no explosive present. The analyses in this paper are based on normal incident waves.

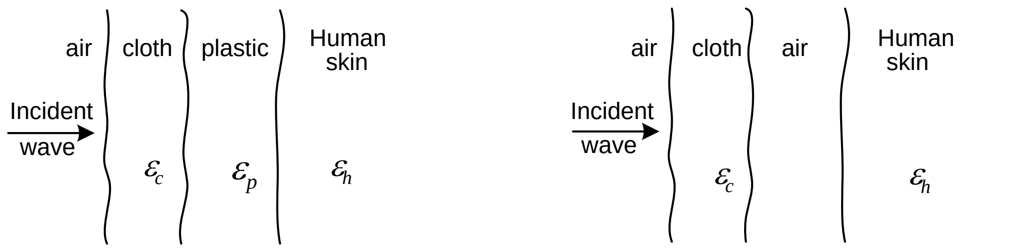


Fig. 1: Multi-layer media model for hidden objects underneath clothing.

First, we find the properties of the materials of interest. The dielectric models are based on the Debye model with parameters fitted experimentally. In the MMW range, the dielectric model for plastic explosive composite (C-4) is given by Federici [2]

$$\varepsilon_{p\_MMW}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + j\omega\tau_1} + \frac{\varepsilon_2 - \varepsilon_3}{1 + j\omega\tau_2} + \frac{\varepsilon_3 - \varepsilon_\infty}{1 + j\omega\tau_3}, \quad (1)$$

where $\varepsilon_s = 3$, $\varepsilon_2 = 2.97$, $\varepsilon_3 = 2.94$, $\varepsilon_\infty = 2.9$, $\tau_1 = 1/(0.72\text{ THz})$, $\tau_2 = 1/(1.26\text{ THz})$, and $\tau_3 = 1/(1.73\text{ THz})$. This is an extension to lower frequencies of the model used for the sub-terahertz range. The range of validity is approximately 100 GHz to 3 THz. For the terahertz range, we employ the dielectric constant model for C-4 from Yamamoto [3]

$$\varepsilon_{p\_THz} = \varepsilon' - j\varepsilon'',$$

$$\varepsilon'(v) = \varepsilon_1 + \sum_j \frac{S_j v_j^2 \left(v_j^2 - v^2\right)}{\left(v_j^2 - v^2\right)^2 + \left(\frac{\Gamma_j}{2\pi c}\right)^2 v^2}, \quad \varepsilon''(v) = \sum_j \frac{S_j v_j^2 \left(\frac{\Gamma_j}{2\pi c}\right) v}{\left(v_j^2 - v^2\right)^2 + \left(\frac{\Gamma_j}{2\pi c}\right)^2 v^2}, \qquad (2)$$

where $\varepsilon_1 = 2.9$, $v = f/c$ with $c = 3\times10^{10}$ cm/s. The refractive index (n) is defined by $n = \mathrm{Re}[\sqrt{\varepsilon}]$. The fitting parameters for this model are shown in Table 1. The extinction coefficient (κ) is defined by $\kappa = \mathrm{Im}[\sqrt{\varepsilon}]$. The absorption coefficient (α) is defined by $\alpha = 4\pi v\kappa / \ln(10)$. Fig. 2 shows the refractive index and absorption coefficient of plastic explosive material (C-4) as a function of frequency based on the model by Yamamoto [3]. The absorption features are distinct among explosive types and are considered important for identification of specific kinds of explosive [3]. An independent investigation by Huang [4] reveals the same absorption features of C-4.

Table 1: Fitting parameter for C-4 in terahertz range [3]

$v_j\left[cm^{-1}\right]$	α (at the peaks) $\left[cm^{-1}\right]$	$S_j[10^{-2}]$	$\Gamma_j/2\pi c\left[cm^{-1}\right]$
26.9	42.7	26.3	7.3
35.5	21.3	1.4	3.6
45.2	31.2	3.4	6.3
51.0	30.7	3.2	8.6
65.7	~50	5.0	10.8
74.8	~43	1.9	10.9

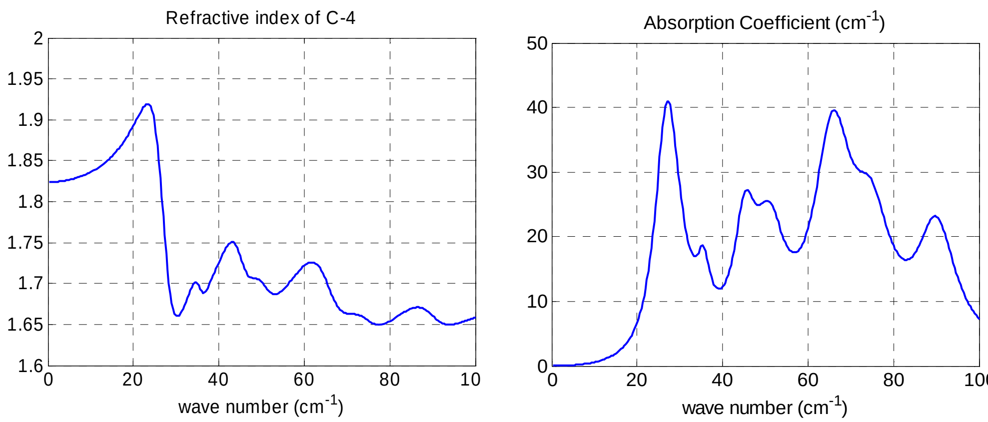


Fig. 2: Index of refraction and the absorption coefficient of C-4 in the terahertz range.

The human skin dielectric model in the MMW range is given by Ghandi [5]

$$\varepsilon_{h\_MMW}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} + \frac{\sigma}{j\omega\varepsilon_o}, \tag{3}$$

where $\varepsilon_\infty = 4.0$, $\varepsilon_s = 42.0$, $\tau = 6.9\times10^{-12}$s, the permittivity of free space $\varepsilon_o = 8.85\times10^{-12}$ F/m, and the conductivity of the skin $\sigma = 1.4$ S/m . It can be compared with experimental data from Alabaster [6], which is shown in Fig. 3.

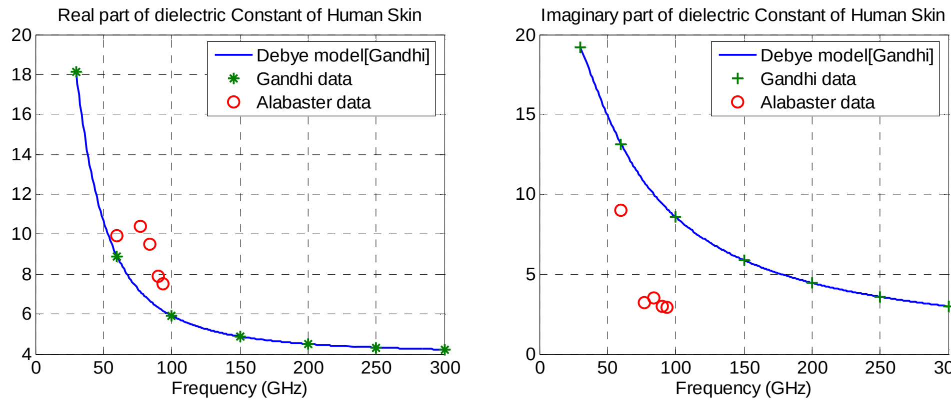


Fig. 3: Dielectric constant of human skin in the MMW range.

For the dielectric model of human skin in the terahertz range, we apply the Double Debye model given by Pickwell [7]

$$\varepsilon_{h\_THz}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + j\omega\tau_1} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + j\omega\tau_2}, \tag{4}$$

where $\varepsilon_s = 58$, $\varepsilon_2 = 3.6$, $\varepsilon_\infty = 3$, $\tau_1 = 9.4$ ps, and $\tau_2 = 0.18$ ps . It is compared with experimental data from Fitzgerald [8] which is shown in Fig. 4.

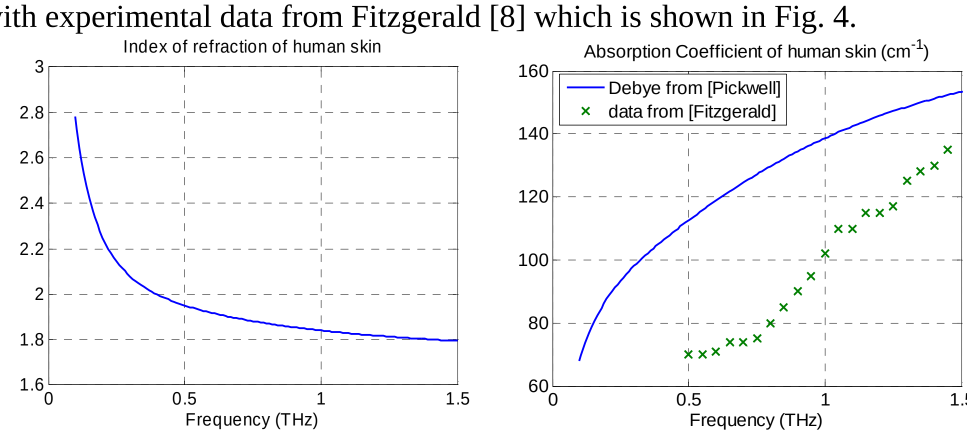


Fig. 4: Index of refraction and absorption coefficient for human skin in the terahertz range.

For cloth, we use cotton with a dielectric constant $\varepsilon_c = 1.9586 - j\,0.1042$ with a varying thickness of 1.2 mm to 3 mm.

We apply a multi-layer model equivalent to a transmission line model [9]. In each layer, we can calculate the ABCD matrix and the total reflection R_s and the total transmission T_s from the multi-layer media given by

$$R_s = \frac{A + B/Z_4 - Z_1\left(C + D/Z_4\right)}{A + B/Z_4 + Z_1\left(C + D/Z_4\right)}, \quad T_s = \frac{2}{A + B/Z_4 + Z_1\left(C + D/Z_4\right)}, \tag{5}$$

where $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix}$, $A_m = D_m = \cos\left(q_m h_m\right)$,

$B_m = jZ_m \sin\left(q_m h_m\right)$, $C_m = j\sin\left(q_m h_m\right)/Z_m$, and h_m is the thickness of the m^{th} layer. The subscript 1 denotes air, subscript 2 denotes cloth, subscript 3 denotes air in configuration A and plastic in configuration B, and subscript 4 represents human skin. Also, the impedance and the propagation constants are given by

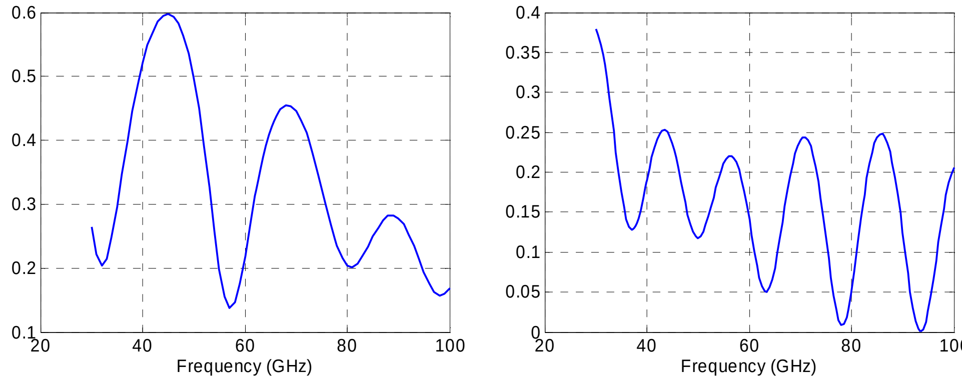
$$Z_m = \frac{\omega \mu_m}{q_m}, \; q_m = \beta_m - j\alpha_m, \tag{6}$$

where μ_m is the permeability, β_m is the propagation constant and α_m is the attenuation constant.

Millimeter and terahertz wave simulation results

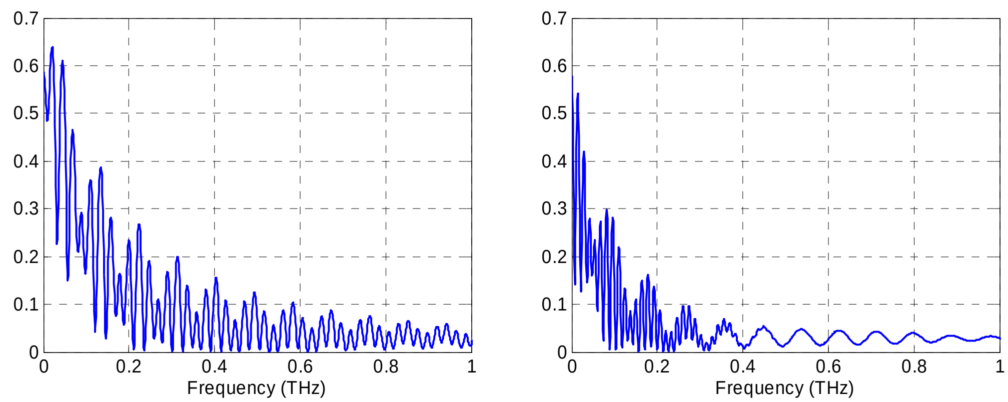
Based on the dielectric constant model and the multi-layer model, we calculate the frequency response in the MMW frequency range in the case where there is no explosive present and the case where there is explosive present. The results are compared in Fig. 5. Because of the larger dielectric constant of the explosive, there is an interference effect creating a rapid change in the frequency response.

The same scenario is simulated for terahertz waves. The results are shown in Fig. 6. Note in Fig. 6(B) that above a frequency of about 0.4 THz, the interference effect from multi-layer scattering disappears because the attenuation of the explosive layer is so high that there is no reflection from human skin. Figs. 5 and 6 show a significant difference in the frequency response in the case where the explosive is present compared to the case where the explosive is not present. This could potentially be used for detection of explosives.



(A) (B)

Fig. 5: Absolute value of reflection coefficient showing frequency response in MMW range: (A) no explosive present, and (B) explosive present. In both cases, the layer thickness is 5 mm.



(A) (B)

Fig. 6: Absolute value of reflection coefficient showing frequency response in THz range: (A) no explosive present, and (B) explosive present. In both cases, the layer thickness is 5 mm.

We have performed reflected pulse simulations in the MMW range with a bandwidth of 10 GHz at several center frequencies (94,140, and 220 GHz) using a unit amplitude pulse. First, we show the pulse characteristics when the plastic explosive layer is present compared to the case where there is no plastic explosive layer (Fig. 7).

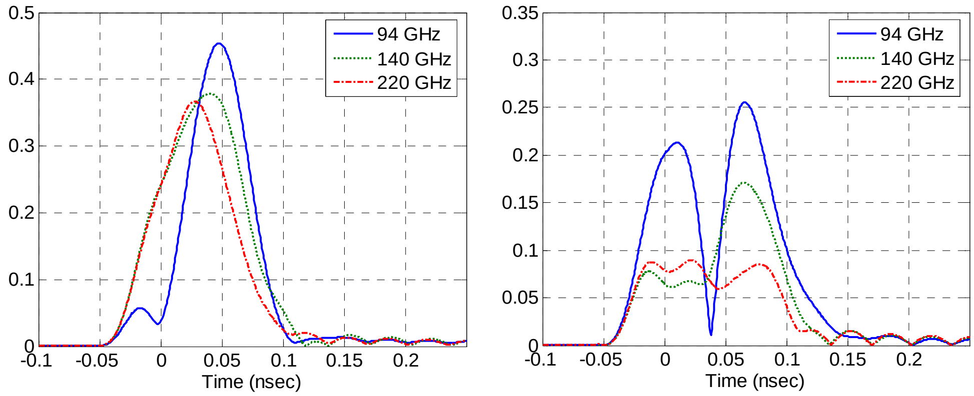


Fig. 7: Reflected pulse simulation in MMW range. A 5 mm layer between the cloth (1.2 mm thickness) and human skin contains air (left) or plastic explosive (right).

In the case where the plastic explosive layer is present, the reflected wave shows two peaks: the first is from the reflection at the interface of the plastic composite layer and cloth layer, and the second is from the interface of the plastic and human skin.

The effect of the thickness of the layers is illustrated in Fig. 8 where we change the thickness of the plastic explosive layer from 5 mm to 10 mm. It shows more delay of the second peak when the plastic explosive layer is thicker. For 220 GHz, the attenuation of the plastic explosive reduces the second peak so much that it may be hard to detect.

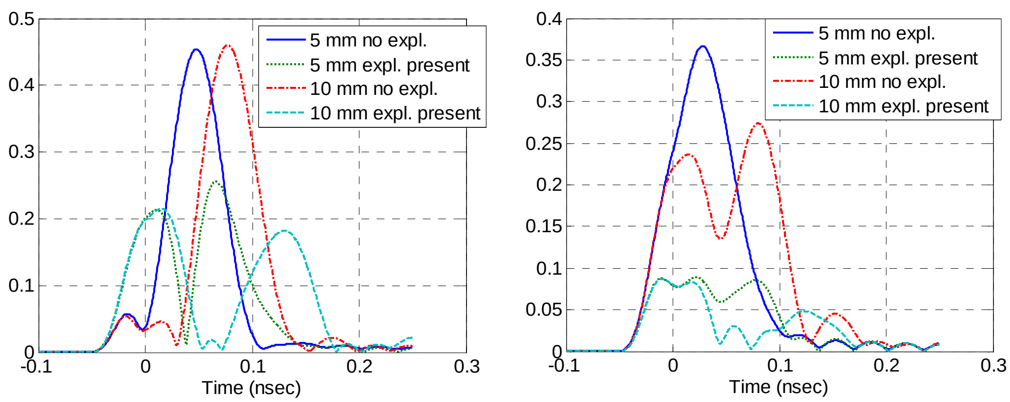


Fig. 8: Effect of thickness of the air or plastic composite layer on reflected pulse. Left: 94 GHz pulse, Right: 220 GHz pulse. In both cases, cloth thickness is 1.2 mm, and the bandwidth is 10 GHz.

We also investigate the effect of cloth thickness to the response. The results at 140 GHz are shown in Fig. 9. With longer propagation in cloth, the peak of the pulse shifts and diminishes.

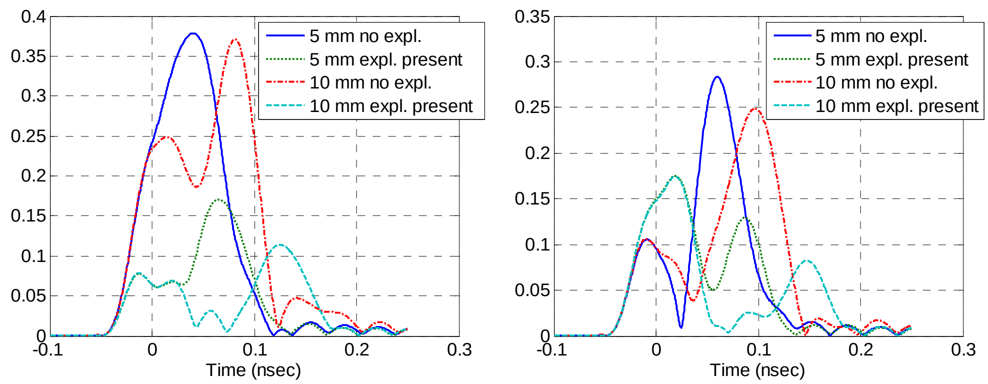


Fig. 9: Effect of thickness of the cloth layer on reflected pulse. Left: cloth thickness = 1.2 mm, Right: cloth thickness = 3 mm. The bandwidth is 10 GHz.

We also perform pulse simulations in the terahertz range where the center frequency is 0.720 THz. The bandwidth of the pulse can be higher than the MMW case and we choose a bandwidth of 50 GHz. The comparison of a 10 GHz bandwidth pulse and 50 GHz bandwidth pulse is shown in Fig. 10. A higher bandwidth pulse gives better resolution of the layer location.

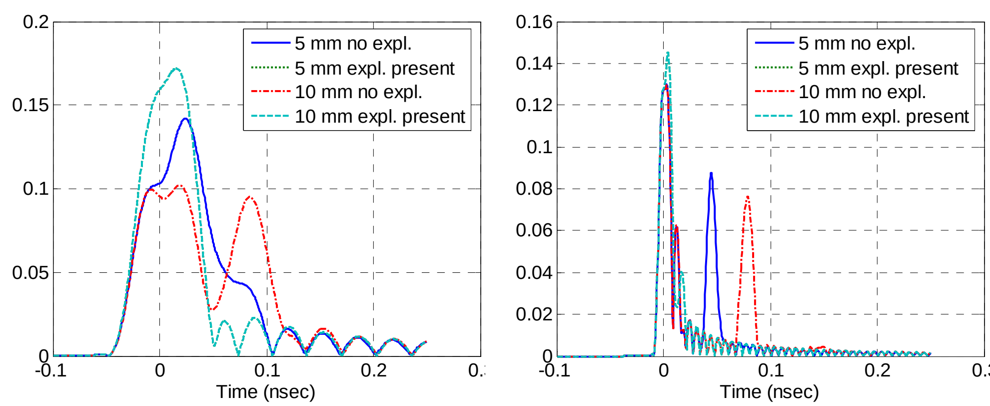


Fig. 10: Comparison of reflected 0.72 THz pulses with different bandwidths. Left: 10 GHz bandwidth, Right: 50 GHz bandwidth. The cloth thickness is 1.2 mm.

In the case where the thickness of the cloth is 3 mm, the simulated pulse is shown in Fig. 11. This shows that when the cloth thickness is large, the reflected pulse contribution from human skin disappears (the second peak). Therefore, with the parameters we have used, terahertz waves will have some limitations for explosive detection, especially when the cloth is thick.

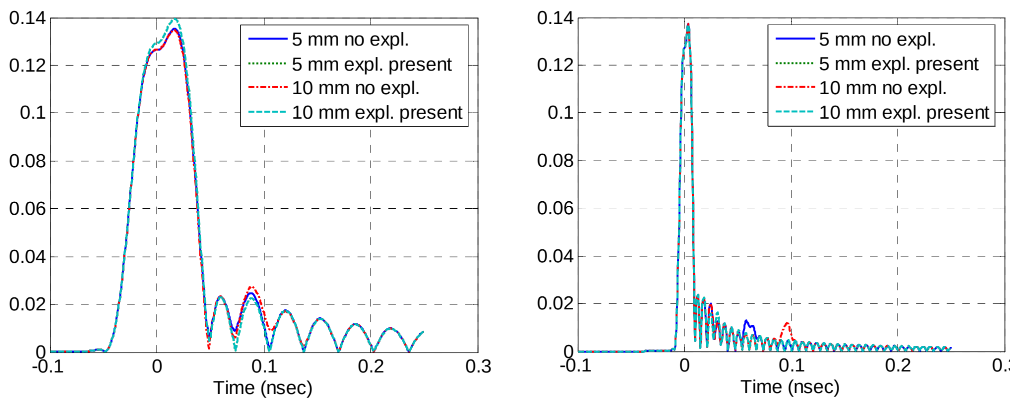


Fig. 11: Reflected 0.72 THz pulses where the cloth thickness is 3 mm.
Left: 10 GHz bandwidth, Right: 50 GHz bandwidth.

Summary

In this paper, we present an electromagnetic model which can be applied to the IED detection problem. The model applies to multi-layer media and is based on a transmission line model. We present simulations of pulse propagation through this multi-layer model and show the potential that pulse reflections may have for detecting the presence of suspicious material underneath clothing.

References

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