An electromagnetic model for plastic composite materials under obscuring layers

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Introduction

Millimeter (MMW) and terahertz wave propagation and imaging through obscuring layers is recently of tremendous interests with practical applications ranging from security, inspection, and surveillance to biological imaging. Both millimeter and terahertz waves show promise in detecting and imaging objects under obscuring material. One important and practical scenario is hidden objects underneath normal clothing in standoff position. An electromagnetic model for this setup is necessary, including the dielectric modeling of materials. We present an electromagnetic model based on multi-layer media. This model includes multiple reflections within each layer, and it has the flexibility to include more complicated structures. Simulations of frequency response and pulse wave through this multi-layer structure are presented. This model provides a tool to estimate the responses at different frequencies and configurations which is instrumental to imaging and detection of objects.

An electromagnetic multi-layer model

The multi-layer model is shown schematically in Figure 1. First, we find the properties of the materials of interest. The dielectric models are based on the Debye model with experimental-fitted parameters. In the MMW range, the dielectric model for plastic explosive (C-4) is given by Federici [1]

$$\varepsilon_{p\_MMW}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{\left[1 + (j\omega\tau_1)\right]} + \frac{\varepsilon_2 - \varepsilon_3}{\left[1 + (j\omega\tau_2)\right]} + \frac{\varepsilon_3 - \varepsilon_\infty}{\left[1 + (j\omega\tau_3)\right]} \tag{1}$$

where $\varepsilon_s = 3$, $\varepsilon_2 = 2.97$, $\varepsilon_3 = 2.94$, $\varepsilon_{\text{inf}} = 2.9$, $\tau_1 = 1/(0.72 \text{ THz})$, $\tau_2 = 1/(1.26 \text{ THz})$, $\tau_3 = 1/(1.73 \text{ THz})$.

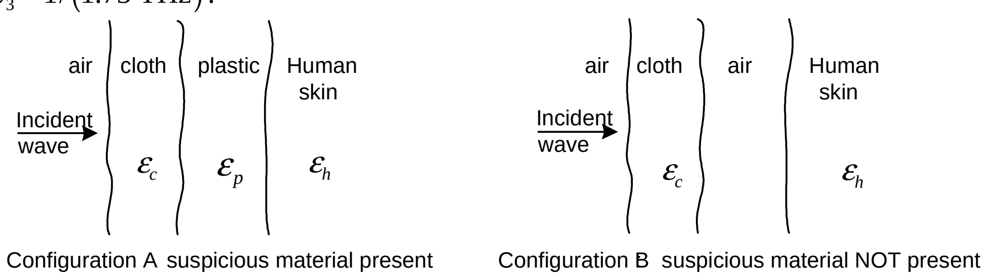

Fig. 1: Multi-layer media model for hidden object underneath clothing

Yamamoto [2] models the dielectric characteristic of C-4 explosive which gives

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

$$\varepsilon'(\nu) = \varepsilon_o + \sum_j \frac{S_j \nu_j^2 \left(\nu_j^2 - \nu^2\right)}{\left(\nu_j^2 - \nu^2\right)^2 + \left(\frac{\Gamma_j}{2\pi c}\right)^2 \nu^2}, \quad \varepsilon''(\nu) = \sum_j \frac{S_j \nu_j^2 \left(\frac{\Gamma_j}{2\pi c}\right)\nu}{\left(\nu_j^2 - \nu^2\right)^2 + \left(\frac{\Gamma_j}{2\pi c}\right)^2 \nu^2} \tag{2}$$

where $v_j, S_j, \Gamma_j/2\pi c$ are extracted from the experimental data and presented in [2]. Its absorption characteristics can be verified with Huang [3]. Note that the wave number is defined by $\nu\left(\text{cm}^{-1}\right) = \dfrac{f\,(\text{Hz})}{c\left(\text{cm/s}\right)} = \dfrac{f}{3\times10^{10}}$.

The human skin dielectric model in MMW range is given by Ghandi [4] (Eq. 3) and can be verified with experimental data from Alabaster [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 $\varepsilon_\infty = 4.0,\ \ \varepsilon_s = 42.0,\ \ \tau = 6.9\times10^{-12}\,\text{s},\ \ \varepsilon_o = 8.85\times10^{-12}\ \text{F/m},\ \ \sigma = 1.4\ \text{S/m}$. For the terahertz range, we apply the Double Debye model [6] given by

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

where $\varepsilon_s = 58,\ \ \varepsilon_2 = 3.6,\ \ \varepsilon_\infty = 3,\ \ \tau_1 = 9.4\ \text{ps, and}\ \tau_2 = 0.18\ \text{ps}$. The experimental data can be verified with [7]. For cloth, we use cotton with a dielectric constant $\varepsilon_c = 1.9586 - j\,0.1042$ and thickness of 1.2 mm.

We apply a multi-layer model equivalent to the transmission line model [8]. 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 which are

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

where $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}\begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix}$, $A_m = D_m = \cos q_m h_m$, $B_m = jZ_m \sin q_m h_m$, $C_m = j\sin q_m h_m / Z_m$. 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

$$Z_m = \frac{\omega\mu_m}{q_m}\ \text{for TE wave},\ Z_m = \frac{q_m}{\omega\mu_m}\ \text{for TM wave},\ q_m = \beta_m\cos\left(\theta_m\right) - j\alpha_m \tag{6}$$

where β_m is the propagation constant, α_m is the attenuation constant, and θ_m is the incident angle of the m^{th} medium.

Millimeter and terahertz wave simulation results

We simulate the reflection back from the multi-layer media based on the dielectric model and the multi-layer transmission line model explained in the previous section. The reflection as a function of frequency in the MMW range is shown in Figure 2 and in the terahertz wave range is shown in Figure 3. In both cases, the layer thickness is 5 mm.

The results show, especially in the terahertz range, that the plastic explosive layer has an obvious effect on the reflection when compared to the case where there is no plastic explosive. It is because the plastic explosive induces more multiple reflection effect and there is a significant loss.

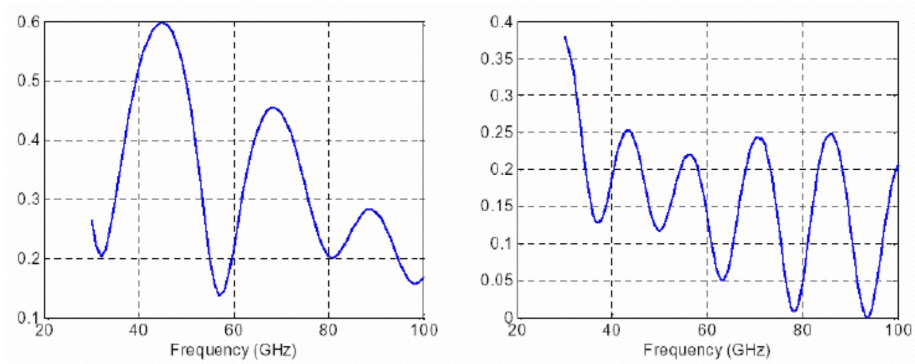

Fig. 2: Reflection in MMW range. Left: no explosive, Right: explosive present

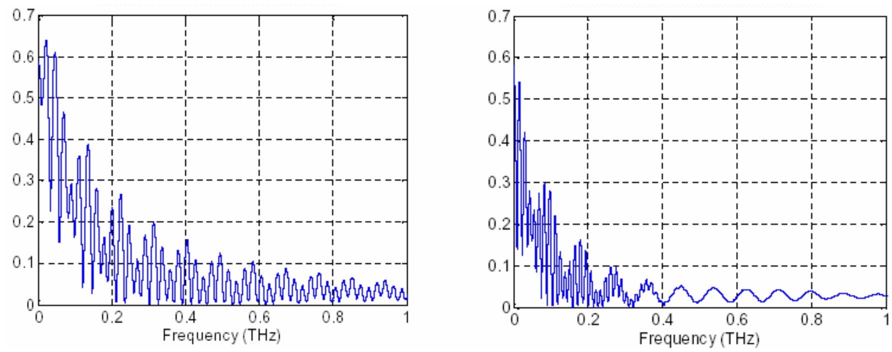

Fig. 3: Reflection in terahertz range. Left: no explosive, Right: explosive present

We also perform reflected pulse simulations in the range of MMW with the bandwidth of 10 GHz at several center frequencies (94, 140 and 220 GHz). First, we look at the pulse characteristics when the plastic explosive layer is present compared to the case where there is no bomb layer as shown in Fig. 4.

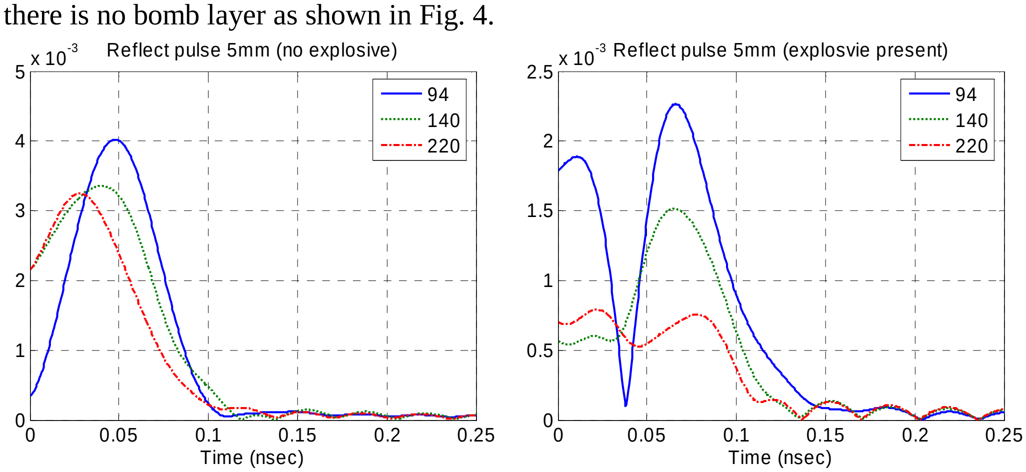

Fig. 4: Pulse simulation in MMW range.

In the case where the plastic explosive layer is present, the pulse shows a second peak from the reflection from the interface of the plastic explosive layer and cloth layer. The reflection from the interface of the plastic explosive and skin is also more delayed compared to the case where the plastic explosive is not present because of the slower wave propagation in the plastic explosive layer. The effect of the thickness of the layers is illustrated in Fig. 5 where we change the thickness of the plastic explosive layer from 5 mm to 10 mm. It shows more delay of the second peak where the plastic explosive layer is thicker. For 220 GHz, the attenuation of the plastic explosive reduces the second peak so much so that it may be hard to detect.

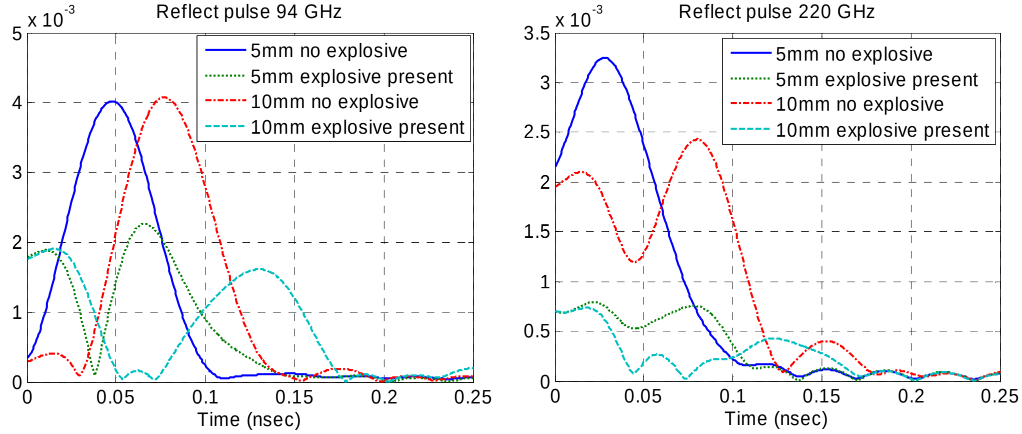

Fig. 5: Effect of thickness of the bomb layer.

Conclusions

In this paper, we present an electromagnetic model for multi-layer media which can be applied to several practical problems. We simulate the case of plastic explosive material underneath normal clothing. We present the dielectric model used for such materials and human skin which are required to build the model. The model is based on the transmission line model which includes multiple reflections. We show the frequency response of the model in both the MMW range and terahertz range. Also, we present pulse simulations through this multi-layer model and show potential that the reflection of pulse may be used to detect the presence of suspicious material underneath clothing.

References:

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