Applied Electromagnetics II Project

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April 25 , 2016

Contents

1.Introduction

In this project, a shielded room was designed such that high frequency waves cannot penetrate into the room. In order to achieve this outcome, the nonmagnetic, non-conducting shield is coated with a conducting material that should reduce the electromagnetic wave by a factor of 10^6 compared to the field outside. The conducting layer may be made of copper, aluminum, mu-metal, or a conducting polymer (Inconel-Alloy 625) based on different priorities. The electromagnetic properties for each of these four materials were found in order to calculate the thickness required for each of them depending on the angle of incidence and polarization of the wave. Then the corresponding cost and density for each of these materials was found. Based on these characteristics (mass, volume, and cost), the materials are compared and the optimal material was selected.

2.Formulas and Material Properties

2.1.Formulas

$$\Gamma_{trans-normal} = \frac{2 * \eta_{material}}{\eta_{space} + \eta_{material}} \tag{1}$$

$$\Gamma_{trans-oblique-perpendicular} = \frac{2\cos\theta_i * \eta_{material}}{\cos\theta_i * \eta_{material} + \cos\theta_t * \eta_{space}} \tag{2}$$

$$\Gamma_{trans-oblique-parallel} = \frac{2\cos\theta_i * \eta_{material}}{\cos\theta_t * \eta_{material} + \cos\theta_i * \eta_{space}} \tag{3}$$

$$\alpha = \sqrt{\pi * f * \mu * \sigma} \tag{4}$$

$$\frac{sin(\theta_i)}{sin(\theta_t)} = \sqrt{\frac{\mu_2 * \epsilon_2}{\mu_1 * \epsilon_1}} \tag{5}$$

$$\eta = (1 + j) * \sqrt{\frac{\omega * \mu}{2 * \sigma}} \tag{6}$$

2.2.Material Properties

Table 1: Properties and Cost of Material

	Conductivity(S/m)	Permeability(H/m)	Density(kg/m^3)	Cost($/kg)
Aluminum	$3.538 * 10^7$	$1.26 * 10^{-6}$	2700	1.598
Copper	$5.85 * 10^7$	$1.26 * 10^{-6}$	8960	4.939
Mu-Metal	$2.0833 * 10^4$	0.1885	8700	65
Inconel-Alloy 625	$77.5 * 10^4$	$1.2608 * 10^{-6}$	8442	11.613

3.Theory

In order, to calculate the minimum thickness required for each conducting material, all angles of incidence should be considered: normal and oblique incidence (parallel and perpendicular polarization). To facilitate that, a MATLAB code was written as shown in the appendix.

3.1.Normal Incident

For the normal incidence case (angle of incidence equal to zero), the characteristic impedance of each material was first calculated (formula 6), then the transmission coefficient (formula), and finally the attenuation (formula 4). Then the thickness was calculated by: $E_t = E_i\Gamma e^{-\alpha d} = E_i 10^{-6}$ For the normal incidence, d is propagating in one direction (z direction). Consequently at $z = d$, $z = \dfrac{-\ln(\dfrac{10^{-6}}{\Gamma})}{\alpha}$ where Γ is the transmission coefficient, z is the thickness of the wall, and α is the attenuation. After a certain distance, z, the electric field intensity will be attenuated by a factor of 10^6; thus, the minimum thickness required will correspond to that distance. Results shown in the appendix table 3.

3.2.Oblique Incident

In the oblique incidence case, the attenuation and the characteristic impedance will be the same. However, the transmission coefficient will depend on the angles of incidence and transmission, and the polarization of the wave as shown in formulae 2 and 3. For the oblique incidence wave oriented in perpendicular or in parallel polarization, the angle of incidence varies from $0 < \theta_i < 90$; therefore, the angle of transmission will be determined using Snell's law (formula 5). Consequently, the thickness will be equal to the projection of d on the z-axis. Consequently at $z = d * cos\theta_t$, $z = \dfrac{-\ln(\dfrac{10^{-6}}{\Gamma})}{\alpha} * cos\theta_t$. Results are shown in the appendix tables 4 to 6 and figures 2 and 3.

4.Implementation

The walls of the room are assumed to be 3 meters tall and 3 meters wide as shown in figure 1. Also, it is assumed that all the walls are equal in size to simplify the calculations. Moreover, the thickness required for each shielded wall is multiplied by the height and width to calculate the volume required for each wall ($Volume = L * W * Thickness$). Then the mass is found by multiplying the volume with the density ($Mass = Volume * Density$) . knowing the total mass of the material, the total cost per wall of the material can calculated

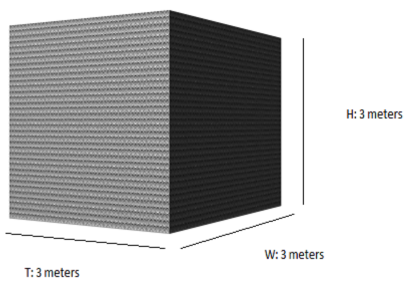

Figure 1: visualization of the room

($TotalCost_{perwall} = Cost_{perKg} * Mass$). Assuming no transmissions from underground the room will require 5 shielded walls.

Table 2: volume mass and cost per shielded wall

	Copper	Aluminum	Mu-Metal	Inconel-Alloy 625
volume(m^3)	$3.40677 * 10^{-4}$	$4.98609 * 10^{-4}$	$2.88891 * 10^{-4}$	$6.47505 * 10^{-3}$
mass(Kg)	3.0525	1.3462	2.5133	54.6624
cost($)	15.0761	2.1513	163.3679	634.7941

From table 2 above, it is clear that the best material in terms of cost and mass is Aluminum, and the best material in terms of volume is Mu-Metal.

5.Appendix

5.1.Results

5.1.1.Normal Results

Table 3: Thickness for normal

Copper	Aluminum	Mu-Metal	Inconel-Alloy 625
3.7859e-05	5.541e-05	3.3275e-05	0.00071961

5.1.2.Perpendicular Polarization Results

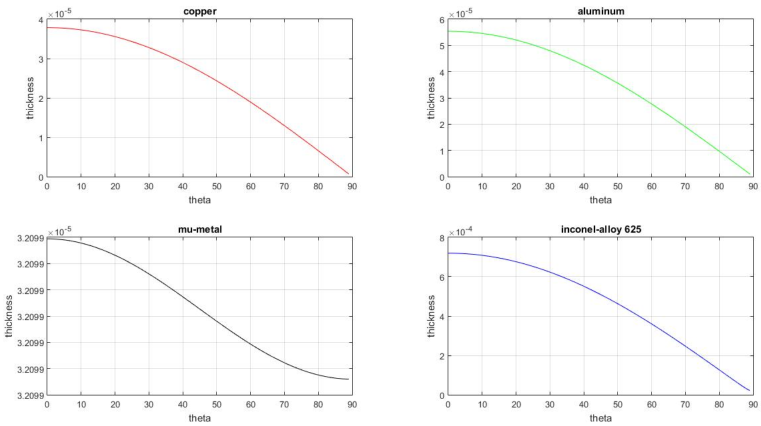

Figure 2: plot for perpendicular

Table 4: Thickness for Perpendicular Polarization

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
1	3.7853e-05	5.5401e-05	3.2099e-05	0.00071945
2	3.7836e-05	5.5376e-05	3.2099e-05	0.00071912
3	3.7807e-05	5.5334e-05	3.2099e-05	0.00071857
4	3.7767e-05	5.5275e-05	3.2099e-05	0.00071781
5	3.7715e-05	5.5199e-05	3.2099e-05	0.00071682
6	3.7651e-05	5.5106e-05	3.2099e-05	0.00071562
7	3.7577e-05	5.4997e-05	3.2099e-05	0.0007142
8	3.749e-05	5.487e-05	3.2099e-05	0.00071256
9	3.7393e-05	5.4727e-05	3.2099e-05	0.00071071
10	3.7284e-05	5.4568e-05	3.2099e-05	0.00070863
11	3.7163e-05	5.4392e-05	3.2099e-05	0.00070635
12	3.7032e-05	5.4199e-05	3.2099e-05	0.00070385
13	3.6889e-05	5.3989e-05	3.2099e-05	0.00070113

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
14	3.6734e-05	5.3764e-05	3.2099e-05	0.0006982
15	3.6569e-05	5.3522e-05	3.2099e-05	0.00069506
16	3.6392e-05	5.3263e-05	3.2099e-05	0.0006917
17	3.6205e-05	5.2988e-05	3.2099e-05	0.00068814
18	3.6006e-05	5.2698e-05	3.2099e-05	0.00068436
19	3.5796e-05	5.2391e-05	3.2099e-05	0.00068038
20	3.5576e-05	5.2068e-05	3.2099e-05	0.00067619
21	3.5344e-05	5.1729e-05	3.2099e-05	0.0006718
22	3.5102e-05	5.1375e-05	3.2099e-05	0.0006672
23	3.4849e-05	5.1005e-05	3.2099e-05	0.00066239
24	3.4586e-05	5.0619e-05	3.2099e-05	0.00065739
25	3.4312e-05	5.0218e-05	3.2099e-05	0.00065219
26	3.4027e-05	4.9802e-05	3.2099e-05	0.00064678
27	3.3732e-05	4.937e-05	3.2099e-05	0.00064118
28	3.3427e-05	4.8924e-05	3.2099e-05	0.00063539
29	3.3112e-05	4.8462e-05	3.2099e-05	0.0006294
30	3.2787e-05	4.7986e-05	3.2099e-05	0.00062322
31	3.2451e-05	4.7495e-05	3.2099e-05	0.00061685
32	3.2106e-05	4.699e-05	3.2099e-05	0.00061029
33	3.1751e-05	4.647e-05	3.2099e-05	0.00060355
34	3.1386e-05	4.5937e-05	3.2099e-05	0.00059662
35	3.1012e-05	4.5389e-05	3.2099e-05	0.00058952
36	3.0628e-05	4.4827e-05	3.2099e-05	0.00058223
37	3.0235e-05	4.4252e-05	3.2099e-05	0.00057476
38	2.9833e-05	4.3663e-05	3.2099e-05	0.00056712
39	2.9422e-05	4.3061e-05	3.2099e-05	0.00055931
40	2.9002e-05	4.2446e-05	3.2099e-05	0.00055133
41	2.8572e-05	4.1818e-05	3.2099e-05	0.00054318
42	2.8135e-05	4.1177e-05	3.2099e-05	0.00053487
43	2.7688e-05	4.0524e-05	3.2099e-05	0.00052639
44	2.7233e-05	3.9858e-05	3.2099e-05	0.00051775
45	2.677e-05	3.9181e-05	3.2099e-05	0.00050896
46	2.6299e-05	3.8491e-05	3.2099e-05	0.00050001
47	2.582e-05	3.7789e-05	3.2099e-05	0.00049091
48	2.5333e-05	3.7076e-05	3.2099e-05	0.00048166
49	2.4838e-05	3.6352e-05	3.2099e-05	0.00047226
50	2.4335e-05	3.5617e-05	3.2099e-05	0.00046272
51	2.3825e-05	3.487e-05	3.2099e-05	0.00045304
52	2.3308e-05	3.4114e-05	3.2099e-05	0.00044322
53	2.2784e-05	3.3346e-05	3.2099e-05	0.00043327
54	2.2253e-05	3.2569e-05	3.2099e-05	0.00042319
55	2.1715e-05	3.1782e-05	3.2099e-05	0.00041297
56	2.117e-05	3.0985e-05	3.2099e-05	0.00040264
57	2.0619e-05	3.0178e-05	3.2099e-05	0.00039218
58	2.0062e-05	2.9363e-05	3.2099e-05	0.0003816
59	1.9499e-05	2.8538e-05	3.2099e-05	0.00037091
60	1.8929e-05	2.7705e-05	3.2099e-05	0.0003601

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
61	1.8354e-05	2.6863e-05	3.2099e-05	0.00034919
62	1.7774e-05	2.6013e-05	3.2099e-05	0.00033817
63	1.7188e-05	2.5155e-05	3.2099e-05	0.00032705
64	1.6596e-05	2.429e-05	3.2099e-05	0.00031583
65	1.6e-05	2.3417e-05	3.2099e-05	0.00030452
66	1.5399e-05	2.2537e-05	3.2099e-05	0.00029311
67	1.4793e-05	2.165e-05	3.2099e-05	0.00028162
68	1.4182e-05	2.0757e-05	3.2099e-05	0.00027005
69	1.3567e-05	1.9857e-05	3.2099e-05	0.00025839
70	1.2948e-05	1.8951e-05	3.2099e-05	0.00024666
71	1.2326e-05	1.804e-05	3.2099e-05	0.00023486
72	1.1699e-05	1.7123e-05	3.2099e-05	0.00022299
73	1.1069e-05	1.62e-05	3.2099e-05	0.00021105
74	1.0435e-05	1.5273e-05	3.2099e-05	0.00019906
75	9.7986e-06	1.4341e-05	3.2099e-05	0.00018701
76	9.1589e-06	1.3405e-05	3.2099e-05	0.00017491
77	8.5164e-06	1.2464e-05	3.2099e-05	0.00016277
78	7.8713e-06	1.152e-05	3.2099e-05	0.00015059
79	7.2238e-06	1.0573e-05	3.2099e-05	0.00013838
80	6.5741e-06	9.6218e-06	3.2099e-05	0.00012615
81	5.9224e-06	8.668e-06	3.2099e-05	0.0001139
82	5.2689e-06	7.7115e-06	3.2099e-05	0.00010165
83	4.6138e-06	6.7527e-06	3.2099e-05	8.9419e-05
84	3.9573e-06	5.7919e-06	3.2099e-05	7.7229e-05
85	3.2996e-06	4.8293e-06	3.2099e-05	6.5124e-05
86	2.6409e-06	3.8652e-06	3.2099e-05	5.3183e-05
87	1.9814e-06	2.8999e-06	3.2099e-05	4.1567e-05
88	1.3213e-06	1.9338e-06	3.2099e-05	3.0671e-05
89	6.6073e-07	9.6703e-07	3.2099e-05	2.1635e-05

5.1.3.Parallel Polarization Results

Table 6: Thickness for Parallel Polarization

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
1	3.7853e-05	5.5401e-05	3.3226e-05	0.0007195
2	3.7836e-05	5.5376e-05	3.3226e-05	0.00071918
3	3.7807e-05	5.5334e-05	3.3226e-05	0.00071863
4	3.7767e-05	5.5275e-05	3.3226e-05	0.00071786
5	3.7715e-05	5.5199e-05	3.3226e-05	0.00071688
6	3.7651e-05	5.5106e-05	3.3226e-05	0.00071567
7	3.7577e-05	5.4997e-05	3.3226e-05	0.00071425
8	3.749e-05	5.487e-05	3.3226e-05	0.00071261
9	3.7393e-05	5.4727e-05	3.3226e-05	0.00071076
10	3.7284e-05	5.4568e-05	3.3226e-05	0.00070869
11	3.7163e-05	5.4392e-05	3.3226e-05	0.0007064

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
12	3.7032e-05	5.4199e-05	3.3226e-05	0.0007039
13	3.6889e-05	5.3989e-05	3.3226e-05	0.00070118
14	3.6734e-05	5.3764e-05	3.3226e-05	0.00069825
15	3.6569e-05	5.3522e-05	3.3226e-05	0.00069511
16	3.6392e-05	5.3263e-05	3.3226e-05	0.00069175
17	3.6205e-05	5.2988e-05	3.3226e-05	0.00068819
18	3.6006e-05	5.2698e-05	3.3226e-05	0.00068441
19	3.5796e-05	5.2391e-05	3.3226e-05	0.00068043
20	3.5576e-05	5.2068e-05	3.3226e-05	0.00067624
21	3.5344e-05	5.1729e-05	3.3226e-05	0.00067185
22	3.5102e-05	5.1375e-05	3.3226e-05	0.00066725
23	3.4849e-05	5.1005e-05	3.3226e-05	0.00066244
24	3.4586e-05	5.0619e-05	3.3226e-05	0.00065744
25	3.4312e-05	5.0218e-05	3.3226e-05	0.00065223
26	3.4027e-05	4.9802e-05	3.3226e-05	0.00064683
27	3.3732e-05	4.937e-05	3.3226e-05	0.00064123
28	3.3427e-05	4.8924e-05	3.3226e-05	0.00063543
29	3.3112e-05	4.8462e-05	3.3226e-05	0.00062945
30	3.2787e-05	4.7986e-05	3.3226e-05	0.00062327
31	3.2451e-05	4.7495e-05	3.3226e-05	0.0006169
32	3.2106e-05	4.699e-05	3.3226e-05	0.00061034
33	3.1751e-05	4.647e-05	3.3226e-05	0.00060359
34	3.1386e-05	4.5937e-05	3.3226e-05	0.00059667
35	3.1012e-05	4.5389e-05	3.3226e-05	0.00058956
36	3.0628e-05	4.4827e-05	3.3226e-05	0.00058227
37	3.0235e-05	4.4252e-05	3.3226e-05	0.00057481
38	2.9833e-05	4.3663e-05	3.3226e-05	0.00056717
39	2.9422e-05	4.3061e-05	3.3226e-05	0.00055935
40	2.9002e-05	4.2446e-05	3.3226e-05	0.00055137
41	2.8572e-05	4.1818e-05	3.3226e-05	0.00054322
42	2.8135e-05	4.1177e-05	3.3226e-05	0.00053491
43	2.7688e-05	4.0524e-05	3.3226e-05	0.00052643
44	2.7233e-05	3.9858e-05	3.3226e-05	0.00051779
45	2.677e-05	3.9181e-05	3.3226e-05	0.000509
46	2.6299e-05	3.8491e-05	3.3226e-05	0.00050005
47	2.582e-05	3.7789e-05	3.3226e-05	0.00049094
48	2.5333e-05	3.7076e-05	3.3226e-05	0.00048169
49	2.4838e-05	3.6352e-05	3.3226e-05	0.0004723
50	2.4335e-05	3.5617e-05	3.3226e-05	0.00046276
51	2.3825e-05	3.487e-05	3.3226e-05	0.00045307
52	2.3308e-05	3.4114e-05	3.3226e-05	0.00044326
53	2.2784e-05	3.3346e-05	3.3226e-05	0.0004333
54	2.2253e-05	3.2569e-05	3.3226e-05	0.00042322
55	2.1715e-05	3.1782e-05	3.3226e-05	0.00041301
56	2.117e-05	3.0985e-05	3.3226e-05	0.00040267
57	2.0619e-05	3.0178e-05	3.3226e-05	0.00039221
58	2.0062e-05	2.9363e-05	3.3226e-05	0.00038163

θ	**Copper**	**Aluminum**	**Mu-Metal**	**Inconel-Alloy 625**
59	1.9499e-05	2.8538e-05	3.3226e-05	0.00037094
60	1.8929e-05	2.7705e-05	3.3226e-05	0.00036013
61	1.8354e-05	2.6863e-05	3.3226e-05	0.00034922
62	1.7774e-05	2.6013e-05	3.3226e-05	0.0003382
63	1.7188e-05	2.5155e-05	3.3226e-05	0.00032707
64	1.6596e-05	2.429e-05	3.3226e-05	0.00031586
65	1.6e-05	2.3417e-05	3.3226e-05	0.00030454
66	1.5399e-05	2.2537e-05	3.3226e-05	0.00029314
67	1.4793e-05	2.165e-05	3.3226e-05	0.00028164
68	1.4182e-05	2.0757e-05	3.3226e-05	0.00027007
69	1.3567e-05	1.9857e-05	3.3226e-05	0.00025841
70	1.2948e-05	1.8951e-05	3.3226e-05	0.00024668
71	1.2326e-05	1.804e-05	3.3226e-05	0.00023487
72	1.1699e-05	1.7123e-05	3.3226e-05	0.000223
73	1.1069e-05	1.62e-05	3.3226e-05	0.00021107
74	1.0435e-05	1.5273e-05	3.3226e-05	0.00019907
75	9.7986e-06	1.4341e-05	3.3226e-05	0.00018703
76	9.1589e-06	1.3405e-05	3.3226e-05	0.00017493
77	8.5164e-06	1.2464e-05	3.3226e-05	0.00016279
78	7.8713e-06	1.152e-05	3.3226e-05	0.00015061
79	7.2238e-06	1.0573e-05	3.3226e-05	0.00013839
80	6.5741e-06	9.6218e-06	3.3226e-05	0.00012616
81	5.9224e-06	8.668e-06	3.3226e-05	0.00011391
82	5.2689e-06	7.7115e-06	3.3226e-05	0.00010166
83	4.6138e-06	6.7527e-06	3.3226e-05	8.9426e-05
84	3.9573e-06	5.7919e-06	3.3226e-05	7.7235e-05
85	3.2996e-06	4.8293e-06	3.3226e-05	6.5129e-05
86	2.6409e-06	3.8652e-06	3.3226e-05	5.3187e-05
87	1.9814e-06	2.8999e-06	3.3226e-05	4.157e-05
88	1.3213e-06	1.9338e-06	3.3226e-05	3.0673e-05
89	6.6073e-07	9.6703e-07	3.3226e-05	2.1637e-05

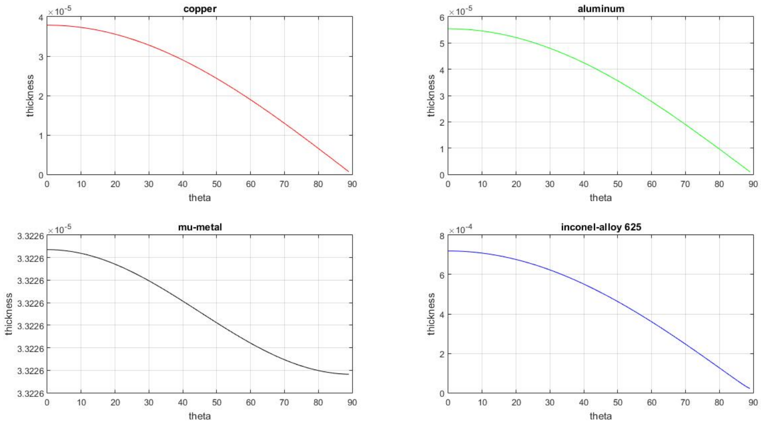

Figure 3: plot for parallel

5.2.Matlab Code

5.2.1.Normal

```
clc
clear
u = 1.256637e-6;%permeability of free space
f = 10e6;% frequency
ettaSpace = 376.7;% etta is characterictic impedance
%copper normal
sigCopp = 5.85*1e7; %sig is conductivity
uRCopp = 1; % uR is relative permeability
ettaCopp = abs((1 + j)*(((2*pi*f*u*uRCopp)/(2*sigCopp))^0.5));
TransCopp = abs((2*ettaCopp)/(ettaSpace+ettaCopp));
attenCopp = (pi*f*u*uRCopp*sigCopp)^0.5;
thickCopp = (log(1e-6/TransCopp))/(-attenCopp);
%aluminum normal
sigAl = 3.538*1e7;
uRAl = 1;
ettaAl = abs((1 + j)*(((2*pi*f*u*uRAl)/(2*sigAl))^0.5));
TransAl = abs((2*ettaAl)/(ettaSpace+ettaAl));
attenAl = (pi*f*u*uRAl*sigAl)^0.5;
thickAl = (log(1e-6/TransAl))/(-attenAl);
%mu metal normal
sigMu = 2.0833*1e4;
uRMu = 1.5e5;
ettaMu = abs((1 + j)*(((2*pi*f*u*uRMu)/(2*sigMu))^0.5));
TransMu = abs((2*ettaMu)/(ettaSpace+ettaMu));
attenMu = (pi*f*u*uRMu*sigMu)^0.5;
thickMu = (log(1e-6/TransMu))/(-attenMu);
%inconel-alloy 625
```

```
sigInc = 77.5*1e4;
uRInc = 1.0006;
ettaInc = abs((1 + j)*(((2*pi*f*u*uRInc)/(2*sigInc))^0.5));
TransInc = abs((2*ettaInc)/(ettaSpace+ettaInc));
attenInc = (pi*f*u*uRInc*sigInc)^0.5;
thickInc = (log(1e-6/TransInc))/(-attenInc);
%exporting
thickvect = [thickCopp  thickAl  thickMu thickInc];%results vector

csvwrite('resultsnormal.csv',thickvect);
```

5.2.2.Oblique Perpendicular

```
clc
clear
u = 1.256637e-6;%permeability of free space
ettaSpace = 376.7;% etta is characterictic impedance
f = 10e6;% frequency
thetaI = 0:1:89;
%Copper
uRCopp = 1;
sigCopp = 5.85*1e7; %sig is conductivity
thetaTCopp = asind(sind(thetaI)/(uRCopp)^0.5); %theta transmitted is got using Snell's law
ettaCopp = abs((1 + j)*(((2*pi*f*u*uRCopp)/(2*sigCopp))^0.5));
TransCopp = abs((2*ettaCopp*cosd(thetaI))/(ettaSpace*cosd(thetaTCopp)+ettaCopp*cosd(thetaI)));
attenCopp = (pi*f*u*uRCopp*sigCopp)^0.5;
thickCopp = ((log(1e-6/TransCopp))/(-attenCopp))*cosd(thetaTCopp);
%aluminum
sigAl = 3.538*1e7;
uRAl = 1;
thetaTAl = asind(sind(thetaI)/(uRAl)^0.5);
ettaAl = abs((1 + j)*(((2*pi*f*u*uRAl)/(2*sigAl))^0.5));
TransAl = abs((2*ettaAl*cosd(thetaI))/(ettaSpace*cosd(thetaTAl)+ettaAl*cosd(thetaI)));
attenAl = (pi*f*u*uRAl*sigAl)^0.5;
thickAl = ((log(1e-6/TransAl))/(-attenAl))*cosd(thetaTAl);
%mu metal
sigMu = 2.0833*1e4;
uRMu = 1.5e5;
thetaTMu = asind(sind(thetaI)/(uRMu)^0.5);
ettaMu = abs((1 + j)*(((2*pi*f*u*uRMu)/(2*sigMu))^0.5));
TransMu = abs((2*ettaMu*cosd(thetaI))/(ettaSpace*cosd(thetaTMu)+ettaMu*cosd(thetaI)));
attenMu = (pi*f*u*uRMu*sigMu)^0.5;
thickMu = ((log(1e-6/TransMu))/(-attenMu))*cosd(thetaTMu);
%inconel-alloy 625
sigInc = 77.5*1e4;
uRInc = 1.0006;
```

```
thetaTinc = asind(sind(thetaI)/(uRInc)^0.5);
ettaInc = abs((1 + j)*(((2*pi*f*u*uRInc)/(2*sigInc))^0.5));
TransInc = abs((2*ettaInc*cosd(thetaI))/(ettaSpace*cosd(thetaTinc)+
    ettaInc*cosd(thetaI)));
attenInc = (pi*f*u*uRInc*sigInc)^0.5;
thickInc = ((log(1e-6/TransInc))/(-attenInc))*cosd(thetaTinc);

thickvec = [thetaI ;thickCopp ; thickAl ;thickMu; thickInc];%results
    vector
thickvec = transpose(thickvec);
figure
subplot(2,2,1),plot(thetaI,thickCopp ,'r');
grid
xlabel('theta')
ylabel('thickness')
title('copper')
subplot(2,2,2),plot(thetaI,thickAl ,'g');
grid
xlabel('theta')
ylabel('thickness')
title('aluminum')
subplot(2,2,3),plot(thetaI,thickMu ,'black');
grid
xlabel('theta')
ylabel('thickness')
title('mu-metal')
subplot(2,2,4),plot(thetaI,thickInc ,'b');
grid
xlabel('theta')
ylabel('thickness')
title('inconel-alloy 625')
%exporting
csvwrite('resultsperpen.csv',thickvec);
```

5.2.3.Oblique Parallel

```
clc
clear
u = 1.256637e-6;%permeability of free space
ettaSpace = 376.7;% etta is characterictic impedance
f = 10e6;% frequency
thetaI = 0:1:89; %theta incident varies between 0 and 90
%Copper
uRCopp = 1;
sigCopp = 5.85*1e7; %sig is conductivity
thetaTCopp = asind(sind(thetaI)/(uRCopp)^0.5); % theta transmitted is
     got using Snell's law
ettaCopp = abs((1 + j)*(((2*pi*f*u*uRCopp)/(2*sigCopp))^0.5));
TransCopp = abs((2*ettaCopp*cosd(thetaI))/(ettaSpace*cosd(thetaI)+
    ettaCopp*cosd(thetaTCopp))); %transmission coefficient for copper
```

```
attenCopp = (pi*f*u*uRCopp*sigCopp)^0.5; %attenuation for copper
thickCopp = ((log(1e-6/TransCopp))/(-attenCopp))*cosd(thetaTCopp); %thickness for copper
%aluminum
sigAl = 3.538*1e7;
uRAl = 1;
thetaTAl = asind(sind(thetaI)/(uRAl)^0.5);
ettaAl = abs((1 + j)*(((2*pi*f*u*uRAl)/(2*sigAl))^0.5));
TransAl = abs((2*ettaAl*cosd(thetaI))/(ettaSpace*cosd(thetaI)+ettaAl*cosd(thetaTAl)))
attenAl = (pi*f*u*uRAl*sigAl)^0.5;
thickAl = ((log(1e-6/TransAl))/(-attenAl))*cosd(thetaTAl);
%mu metal
sigMu = 2.0833*1e4;
uRMu = 1.5e5;
thetaTMu = asind(sind(thetaI)/(uRMu)^0.5);
ettaMu = abs((1 + j)*(((2*pi*f*u*uRMu)/(2*sigMu))^0.5));
TransMu = abs((2*ettaMu*cosd(thetaI))/(ettaSpace*cosd(thetaI)+ettaMu*cosd(thetaTMu)));
attenMu = (pi*f*u*uRMu*sigMu)^0.5;
thickMu = ((log(1e-6/TransMu))/(-attenMu))*cosd(thetaTMu);
%inconel-alloy 625
sigInc = 77.5*1e4;
uRInc = 1.0006;
thetaTinc = asind(sind(thetaI)/(uRInc)^0.5);
ettaInc = abs((1 + j)*(((2*pi*f*u*uRInc)/(2*sigInc))^0.5));
TransInc = abs((2*ettaInc*cosd(thetaI))/(ettaSpace*cosd(thetaI)+ettaInc*cosd(thetaTinc)));
attenInc = (pi*f*u*uRInc*sigInc)^0.5;
thickInc = ((log(1e-6/TransInc))/(-attenInc))*cosd(thetaTinc);

thickvec = [thetaI ;thickCopp ; thickAl ;thickMu; thickInc];%results vector
thickvec = transpose(thickvec);
figure
subplot(2,2,1),plot(thetaI,thickCopp ,'r');
xlabel('theta')
ylabel('thickness')
title('copper')
grid
subplot(2,2,2),plot(thetaI,thickAl ,'g');
grid
xlabel('theta')
ylabel('thickness')
title('aluminum')
subplot(2,2,3),plot(thetaI,thickMu ,'black');
grid
xlabel('theta')
ylabel('thickness')
```

```
title('mu-metal')
subplot(2,2,4),plot(thetaI,thickInc  ,'b');
grid
xlabel('theta')
ylabel('thickness')
title('inconel-alloy 625')
%exporting
csvwrite('resultsparallel.csv',thickvec);
```

6.References

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