

Summary

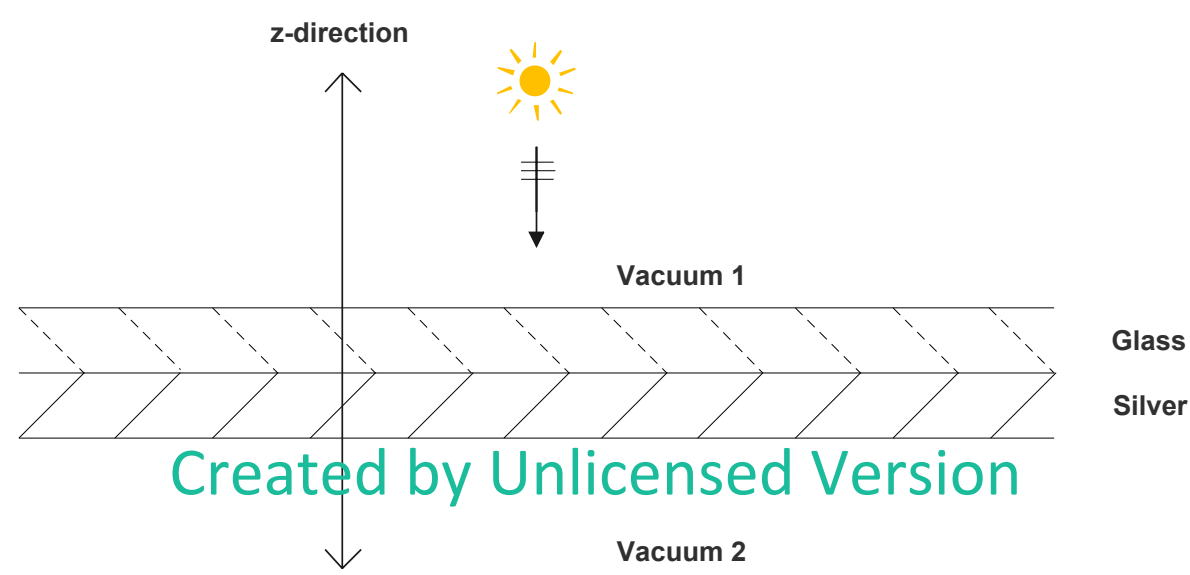
Meta-materials are assemblies of naturally occurring substances which exhibit unusual properties such as zero permeability and/or permittivity, or negative index of refraction. Applications include high sensitivity diagnostics, super-resolution imaging, and cloaking-ing.

Purpose/Goal

Create a Python code that would serve for an open sourced Machine Learning platform TensorFlow. The Python code solves for the Reflective and Transmittance values. Using this and creating a large database of Transmittance values this would allow the Machine Learning system to optimize the best multi-layered material using the users given parameters of: number of materials, type of material, and angle/strength of wavelength projected onto the meta-surface.

Optics Diagram

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About ENZ Materials

EPSILON-NEAR-ZERO METAMATERIALS AND...

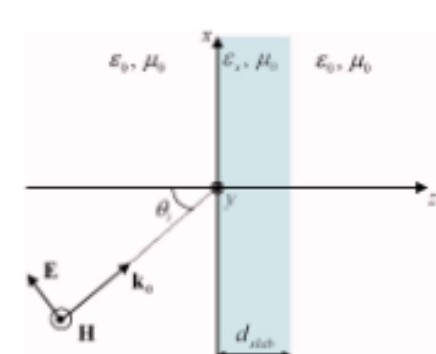


FIG. 2. (Color online) A plane slab of permittivity ϵ_0 excited by a TM plane wave in a suitable Cartesian coordinate system.

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When $\beta=0$, for which particular case $H(0)$ will be constant inside the slab (to fulfill the curl-free condition in Eq. (1)) with value $H(0)=H_0 e^{i\phi} e^{-i\phi} = H_0 e^{i\phi} e^{-i\phi}$. The electric field would decay exponentially inside the slab for $\beta \neq 0$, whereas for normal incidence the electric field, being directed along z , would be linearly varying along z to satisfy Eq. (1) and to match the continuity conditions at the two boundaries.

It is worth understanding how for any $\beta \neq 0$ the $\epsilon_0=0$ slab acts as a perfect magnetic boundary in this geometry, yielding a 180° phase shift for reflection of the magnetic field at the entrance face. The anomalous behavior with partial tunneling of the field at $\beta \neq 0$ is explained with a polaritonic resonance of such a slab, as we discuss in the following.

Fitting the value of the slab permittivity ϵ_0 to a nonzero, but low value, we can study the behavior of the transmission function when the angle of incidence of the impinging plane wave is varied, in order to understand how the limiting discontinuous response predicted by Fig. 2) is reached when ϵ_0 becomes identically zero. In this way, we predict the realistic response of an ENZ plane slab near its plasma frequency to a source excitation, satisfying all the physical constraints of continuity and finiteness of the fields. Also, some physical insights may be gained by this analysis, as we present below.

The transmission coefficient for such a simple problem may be written in compact form as

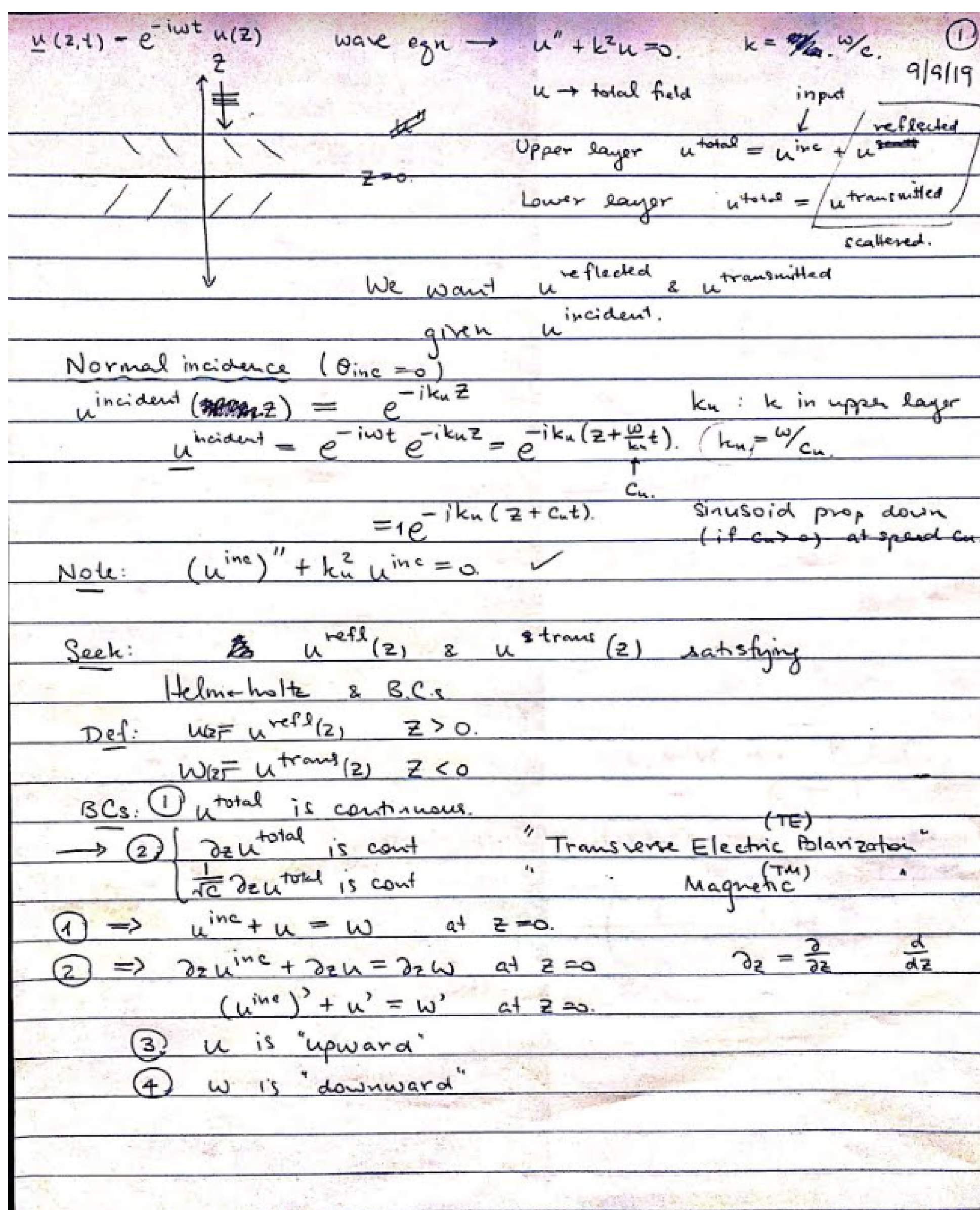
$$T(\beta) = \frac{2\epsilon_0 \cos(k_0 z_0)}{2\epsilon_0 \cos(k_0 z_0) + i\beta \sin(k_0 z_0)} \quad (1)$$

where $k_0 = \sqrt{\epsilon_0} \omega/c$ and $\epsilon_0 = \epsilon_0 - i\beta$. The sign of the square root for k_0 should be chosen to satisfy the radiation condition, i.e., its imaginary part should be non negative, whereas the branch choice for k_0 does not influence the solution of Eq. (1).

Equation (1) clearly shows that the Brewster angle for this problem, which corresponds to the polar angle measured of the structure under analysis, $\theta_B = 90^\circ$ is given by the simple relation $\sin(\theta_B) = \beta/\epsilon_0$ for which $|\beta| \leq 1$. Since we are not considering electrically thick slabs and the wave number in the ENZ slab is small, the only available plasmonic resonance, for which the wave tunnels completely through the slab despite the huge mismatch between free space and the ENZ material, is represented by the condition $\epsilon_0 = -\epsilon_0$.

The "quality factor" Q for this resonance in terms of the "angular fractional bandwidth" may be found by considering the complex root of $\beta = \epsilon_0 + i\beta$ of the denominator in Eq. (1) and is given by $Q = \beta/\epsilon_0$. Interestingly, its value for ENZ materials does not depend on ϵ_0, ϵ_0 and is given by the following closed form expression:

Math required

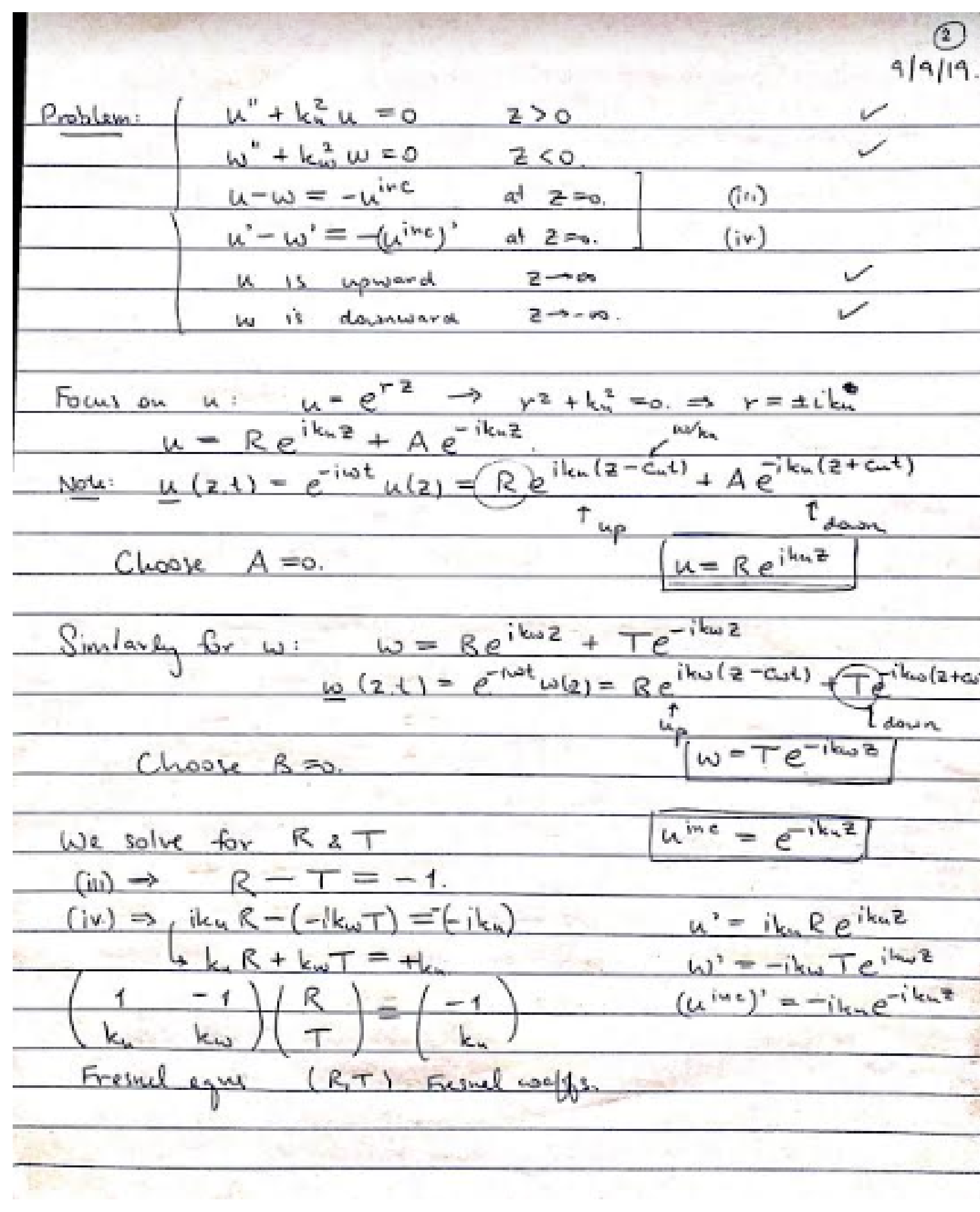


4 Layered Code:

```
1 from numpy import linalg
2 import numpy as np
3 from math import *
4 from cmath import *
5 import matplotlib.pyplot as plt

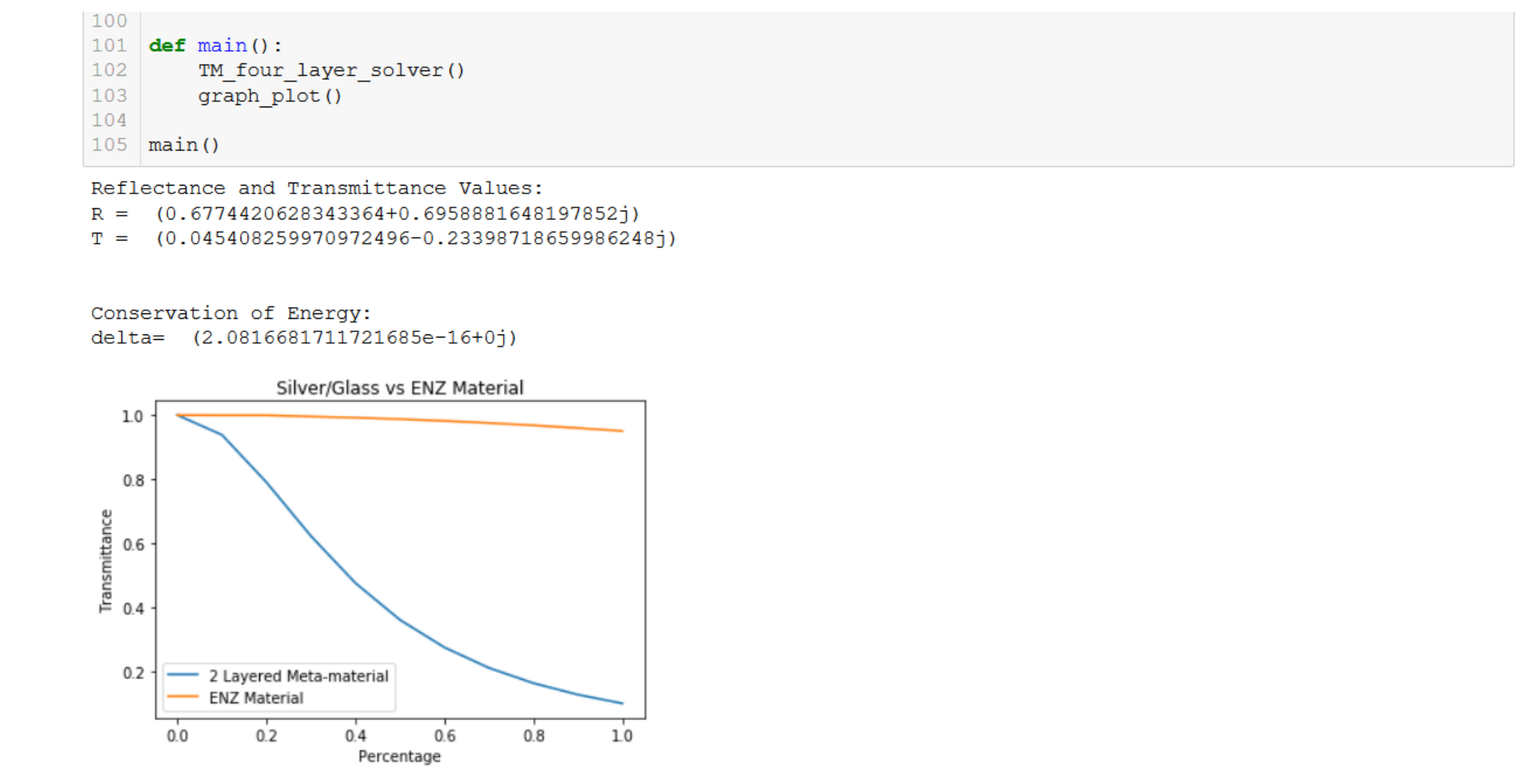
1 def TM_four_layer_solver():
2     #wavelength
3     h = 0.1/2*pi
4     k0 = 2*pi/h
5     ku = 1*k0
6     kv1 = cmath.sqrt(-2)*k0 # Permittivity of Silver is about -23
7     kv2 = cmath.sqrt(-23)*k0 # Permittivity of Glass is about 2.2
8     kw = cmath.sqrt(1)*k0
9
10    a1 = 0
11    a2 = -h/2
12    a3 = -h
13
14    taol = (kv1**2)/(kv1**2)
15    taol2 = (kv1**2)/(kv1**2)
16    taol3 = (kv2**2)/(kv2**2)
17
18    Cu = cos(ku*a1)
19    Su = sin(ku*a1)
20
21    Cv1a1 = cos(kv1*a1)
22    Sv1a1 = sin(kv1*a1)
23    Cv1a2 = cos(kv1*a2)
24    Sv1a2 = sin(kv1*a2)
25
26    Cv2a2 = cos(kv2*a2)
27    Sv2a2 = sin(kv2*a2)
28    Cv2a3 = cos(kv2*a3)
29    Sv2a3 = sin(kv2*a3)
30
31    Cu = cos(ku*a3)
32    Su = sin(ku*a3)
33
34    nrow1 = [ complex(Cu,Su), complex(-Cv1a1,Sv1a1), complex(-Cv1a1,-Sv1a1), 0, 0, 0 ]
35    nrow2 = [ kv1*complex(Cu,Su), kv1*kv1*complex(Cv1a1,-Sv1a1), kv1*kv1*complex(-Cv1a1,Sv1a1), 0, 0, 0 ]
36    nrow3 = [ 0, complex(Cv1a2,-Sv1a2), complex(Cv1a2,Sv1a2), complex(-Cv2a2,Sv2a2), complex(Cv2a2,-Sv2a2), 0 ]
37    nrow4 = [ 0, kv1*complex(-Cv1a2,Sv1a2), kv1*complex(Cv1a2,Sv1a2), kv2*kv2*complex(Cv2a2,-Sv2a2), kv2*kv2*complex(-Cv2a2,Sv2a2), 0 ]
38    nrow5 = [ 0, 0, 0, complex(Cv2a3,Sv2a3), complex(Cv2a3,Sv2a3), complex(-Cw,-Sw) ]
39    nrow6 = [ 0, 0, 0, kv2*complex(-Cv2a3,Sv2a3), kv2*kv2*complex(Cv2a3,Sv2a3), kv2*kv2*complex(Cw,-Sw) ]
40
41    mat = np.array([nrow1,nrow2,nrow3,nrow4,nrow5,nrow6])
42
43    rmat = np.array([nrow1,nrow2,nrow3,nrow4,nrow5,nrow6])
44
45    answer = np.linalg.solve(mat,cons)
46    Rval = answer[0]
47    Tval = answer[1]
48    D1val = answer[2]
49    D2val = answer[3]
50    D3val = answer[4]
51    D4val = answer[5]
52    D5val = answer[6]
53    D6val = answer[7]
54    D7val = answer[8]
55    D8val = answer[9]
56
57    print("Reflection and Transmittance Values: ")
58    print("R = ",Rval)
59    print("T = ",Tval)
60    print("D1 = ",D1val)
61    print("D2 = ",D2val)
62    print("D3 = ",D3val)
63    print("D4 = ",D4val)
64    print("D5 = ",D5val)
65    print("D6 = ",D6val)
66    print("D7 = ",D7val)
67    print("D8 = ",D8val)
```

Math required (cont)



4 Layered Code: (cont)

```
66 #Conservation of Energy
67 eu = (abs(Rval))**2
68 ew = (abs(Tval))**2
69
70 delta = 1 - eu - (kw**2/kv**2)*ew
71 print("\n")
72 print("Conservation of Energy: ")
73 print("delta=",delta)
74
75 def graph_plot():
76    T1 = [0,0,1,0,2,0,3,0,4,0,5,0,6,0,7,0,8,0,9,1,0]
77    T1 = [0.9999999999999999,0.9384076579820084,
78    0.7965907703217033,0.6231062848481449,
79    0.476733236623363,0.362053197970792,
80    0.2760763820156898,0.212254124231262,
81    0.1646021311102665,0.1288566578945607,
82    0.1015570941101024]
83
84    plt.plot(T1,T1, label = "2 Layered Meta-material")
85
86    P2 = [0,0,1,0,2,0,3,0,4,0,5,0,6,0,7,0,8,0,9,1,0]
87    T2 = [0.9999999999999999,0.999496337635457,
88    0.999486537635457,0.999478731117413,
89    0.991664747500382,0.9874637502172039,
90    0.981908084594001,0.975526661556062,
91    0.968113887142562,0.9597567408200651,
92    0.950471112550164]
93
94    plt.plot(P2,T2, label = "ENZ Material")
95
96    plt.xlabel('Percentage')
97    plt.ylabel('Transmittance')
98    plt.title('Silver/Glass vs ENZ Material')
99    plt.legend()
100    plt.show()
```



Improvements

- Some improvements that can be made within this project are:
- Implement a loop or recursive function to solve for many T-Values for the 4 Layer code at once.
- Create a database of many combinations of Meta Materials.
- Create a Multi-Layered code that solves for any number of Layers.

Conclusions

Engineers and others interested in Meta-materials may be able to use this specific 4 Layer code to create a layered structure such as the example provided (Glass/Silver) to find the best proportion of materials that will allow light to transmit through. Thus being able to produce an ENZ-like material.

References

- <https://www.ft.com/content/c6864c76-de7d-11e7-a0d4-0944c5f49e46>
- <https://refractiveindex.info/>
- Andrea and Silveirinha, Epsilon-near-zero metamaterials and electromagnetic sources: Tailoring the radiation phase pattern. PhysRevB.75.155410 (2007) volume 75, issue 15

Super Cloaking Visual

