Mini Project Report

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2018143

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Problem Statement

(a) Design a photonic crystal based waveguide for on-chip applications at 450nm.

(b) How would you change the design parameter if the wavelength of operation is changed to 550nm? Show by numerical computations.

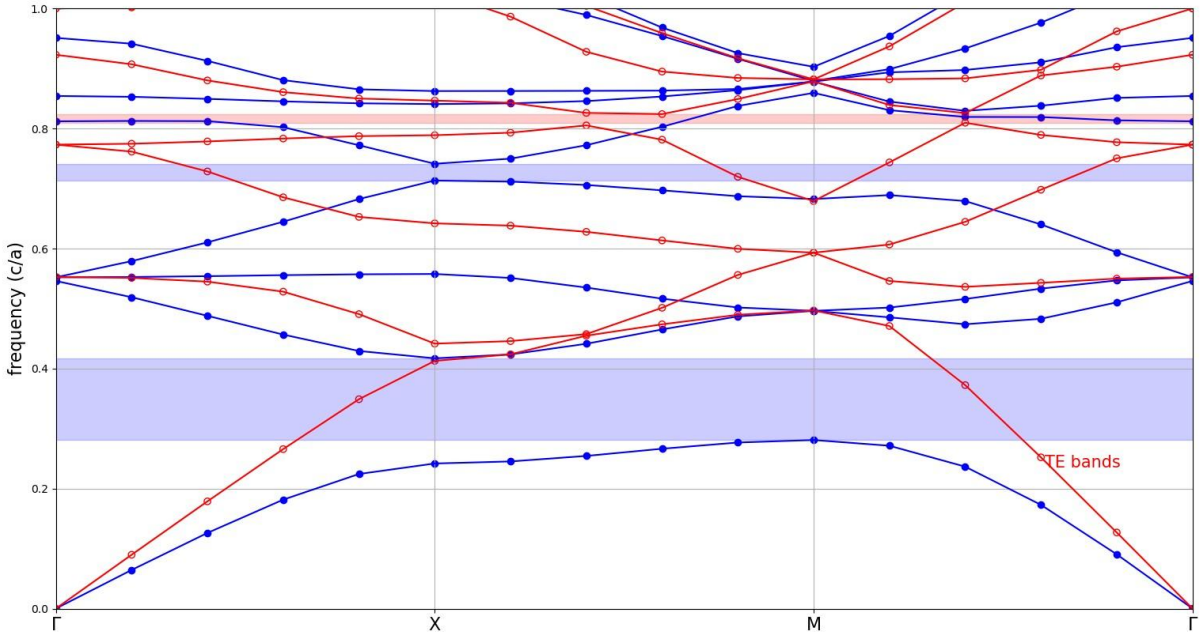
CONTENTS

Code for computing the band diagram and the band gaps for a square lattice of dielectric rods (epsilon =12, radius of rods = 0.2)

```
import math
import meep as mp
from meep import mpb
import matplotlib
#matplotlib.use('Agg')

import matplotlib.pyplot as plt


# Determining the number of eigenstates computed at each k points.
num_bands=50

# k_points=Bloch wavevectors we want to compute the bands at.
# Setting it to the corners of irreducible Brillouin zone.
k_points=[mp.Vector3(),                 # Gamma
          mp.Vector3(0.5),              # X
          mp.Vector3(0.5,0.5),          # M
          mp.Vector3()]                 # Gamma

# Computing bands at a lot of intermediate points to get a continuous band structure
k_points=mp.interpolate(4,k_points)

# Setting up the size of the computational cells
geometry_lattice=mp.Lattice(size=mp.Vector3(1,1))

# Setting up geometric objects at the center of the lattice
geometry=[mp.Cylinder(0.2,material=mp.Medium(epsilon=12))]
geometry = mp.geometric_objects_lattice_duplicates(geometry_lattice, geometry)


# Setting the resolution
resolution=32
```

```
# Creating a ModeSolver object -
ms=mpb.ModeSolver(num_bands=num_bands,
                  k_points=k_points,
                  geometry=geometry,
                  geometry_lattice=geometry_lattice,
                  resolution=resolution)

# Printing and running
print("Square lattice of rods: TE bands")
ms.run_te()

# This outputs the z field components of the tm mode of the wave.
ms.run_tm(mpb.output_efield_z)

# This outputs the magnetic field z components for the te_modes,
# at the point X, and the energy density power (D power).
ms.run_te(mpb.output_at_kpoint(mp.Vector3(0.5),mpb.output_hfield_z,mpb.output_dpwr))

# sample points -

ms.run_te()
te_freqs = ms.all_freqs
te_gaps = ms.gap_list



ms.run_tm()
tm_freqs = ms.all_freqs
tm_gaps = ms.gap_list
print("tm gaps: ", tm_gaps)
print("freqs: ", tm_freqs)

tm_freqs = ms.all_freqs
tm_gaps = ms.gap_list
ms.run_te()
te_freqs = ms.all_freqs
te_gaps = ms.gap_list

import matplotlib.pyplot as plt
```

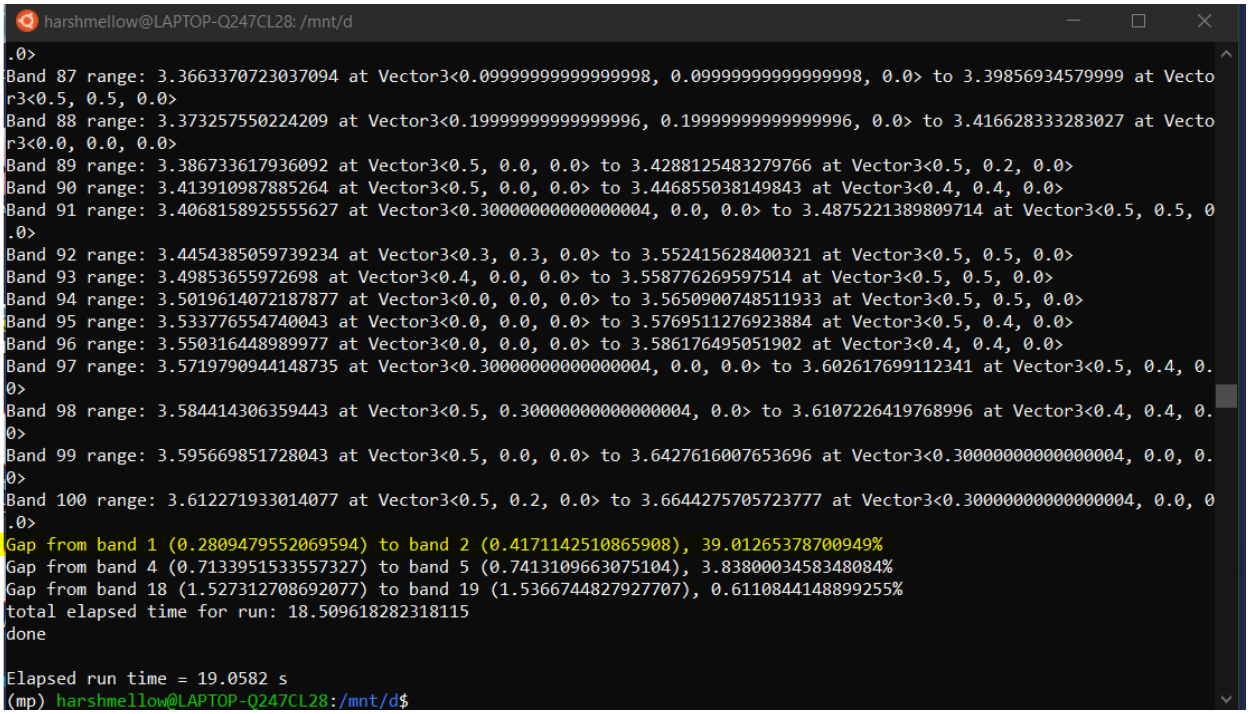
```
fig, ax = plt.subplots()
x = range(len(tm_freqs))
# Plot bands
# Scatter plot for multiple y values, see https://stackoverflow.com/a/34280815/2261298
for xz, tmz, tez in zip(x, tm_freqs, te_freqs):
        ax.scatter([xz]*len(tmz), tmz, color='blue')
        ax.scatter([xz]*len(tez), tez, color='red', facecolors='none')
ax.plot(tm_freqs, color='blue')
ax.plot(te_freqs, color='red')
ax.set_ylim([0, 1])
ax.set_xlim([x[0], x[-1]])

# Plot gaps
for gap in tm_gaps:
        if gap[0] > 1:
        ax.fill_between(x, gap[1], gap[2], color='blue', alpha=0.2)

for gap in te_gaps:
        if gap[0] > 1:
        ax.fill_between(x, gap[1], gap[2], color='red', alpha=0.2)



# Plot labels
#ax.text(12, 0.04, 'TM bands', color='blue', size=15)
ax.text(13.05, 0.235, 'TE bands', color='red', size=15)

points_in_between = (len(tm_freqs) - 4) / 3
tick_locs = [i*points_in_between+i for i in range(4)]
tick_labs = ['Γ', 'X', 'M', 'Γ']
ax.set_xticks(tick_locs)
ax.set_xticklabels(tick_labs, size=16)
ax.set_ylabel('frequency (c/a)', size=16)
ax.grid(True)

plt.show()
```



Basic Band Diagram obtained without the line defects

We get a T.M. band gap from band 1 (0.280947955) to band 2 (0.417114251086).

The mid gap point is : [band 1 (0.280947) + band 2 (0.417114)] /2 = 0.349035



Code creating a line defect waveguide - Simulating for 450 nm

```
import math
import meep as mp
from meep import mpb
import matplotlib
matplotlib.use('Agg')
import matplotlib.pyplot as plt

# Setting the lattice lattice constant
a=0.15706372

# Setting the geometry lattice to be 20*lambda
geometry_lattice = mp.Lattice(size=mp.Vector3(11, 11))

# Setting our rods to be of radius 0.2*lattice_constant
geometry = [mp.Cylinder(0.2*a, material=mp.Medium(epsilon=12))]

# Duplicating our rods through the entire geometric lattice taken
geometry = mp.geometric_objects_lattice_duplicates(geometry_lattice, geometry)

# Creating a line defect through a for loop. This has the same radius=0.2*a.
for i in range(11):
        geometry.append(mp.Cylinder(0.2*a, center=mp.Vector3(1+i), material=mp.air))
        geometry.append(mp.Cylinder(0.2*a, center=mp.Vector3(-(1+i)), material=mp.air))

# Setting Resolution
resolution = 16

# Setting our k-points
k_points = [mp.Vector3(0.5, 0.5)]

# Setting number of eigenstates to calculate our at the wavevectors
num_bands = 100

# Interpolating the k-points
k_points=mp.interpolate(4,k_points)
```

```
# Creating a mode solver object
ms = mpb.ModeSolver(num_bands=num_bands,
                    k_points=k_points,
                    geometry=geometry,
                    geometry_lattice=geometry_lattice,
                    resolution=resolution)

ms.run_tm()




eps = ms.get_epsilon()
plt.imshow(eps.T, interpolation='spline36', cmap='binary')
plt.axis('off')
plt.savefig("pic.png")
```

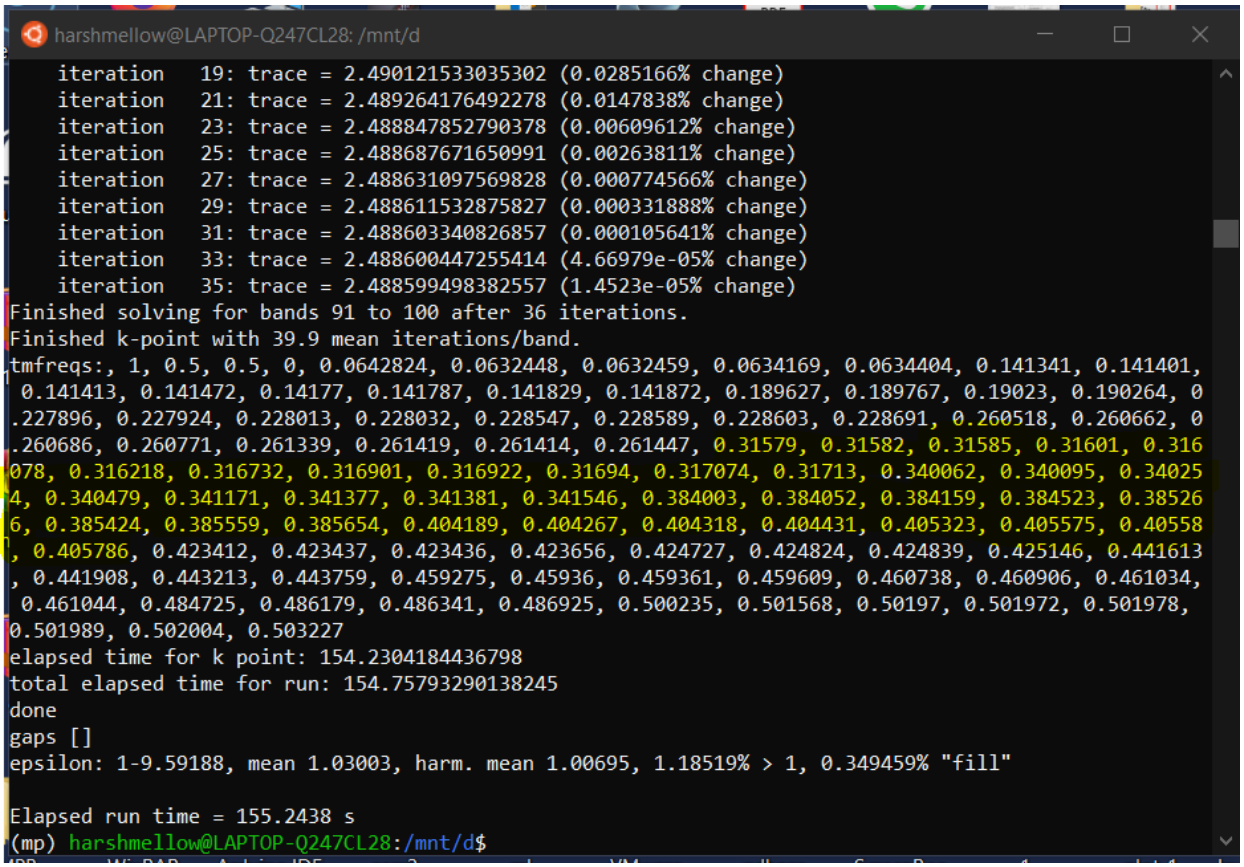
Code creating a line defect waveguide - Simulating for 550 nm

```
import math
import meep as mp
from meep import mpb
import matplotlib
matplotlib.use('Agg')
import matplotlib.pyplot as plt

# Setting the lattice lattice constant
a=0.19196678

# Setting the geometry lattice to be 20*lambda
geometry_lattice = mp.Lattice(size=mp.Vector3(11, 11))

# Setting our rods to be of radius 0.2*lattice_constant
geometry = [mp.Cylinder(0.2*a, material=mp.Medium(epsilon=12))]

# Duplicating our rods through the entire geometric lattice taken
geometry = mp.geometric_objects_lattice_duplicates(geometry_lattice, geometry)

# Creating a line defect through a for loop. This has the same radius=0.2*a.
for i in range(11):
        geometry.append(mp.Cylinder(0.2*a, center=mp.Vector3(1+i), material=mp.air))
        geometry.append(mp.Cylinder(0.2*a, center=mp.Vector3(-(1+i)), material=mp.air))

# Setting Resolution
resolution = 16

# Setting our k-points
k_points = [mp.Vector3(0.5, 0.5)]

# Setting number of eigenstates to calculate our at the wavevectors
num_bands = 100

# Interpolating the k-points
k_points=mp.interpolate(4,k_points)
```

```
# Creating a mode solver object
ms = mpb.ModeSolver(num_bands=num_bands,
                    k_points=k_points,
                    geometry=geometry,
                    geometry_lattice=geometry_lattice,
                    resolution=resolution)

ms.run_tm()




eps = ms.get_epsilon()
plt.imshow(eps.T, interpolation='spline36', cmap='binary')
plt.axis('off')
plt.savefig("pic.png")
```

This diagram shows the line defect formed by a missing row of rods in square lattice of radius 0.2a dielectric rods (epsilon=12) in air.

For 450 nm obtained TM freqs after creating line defect



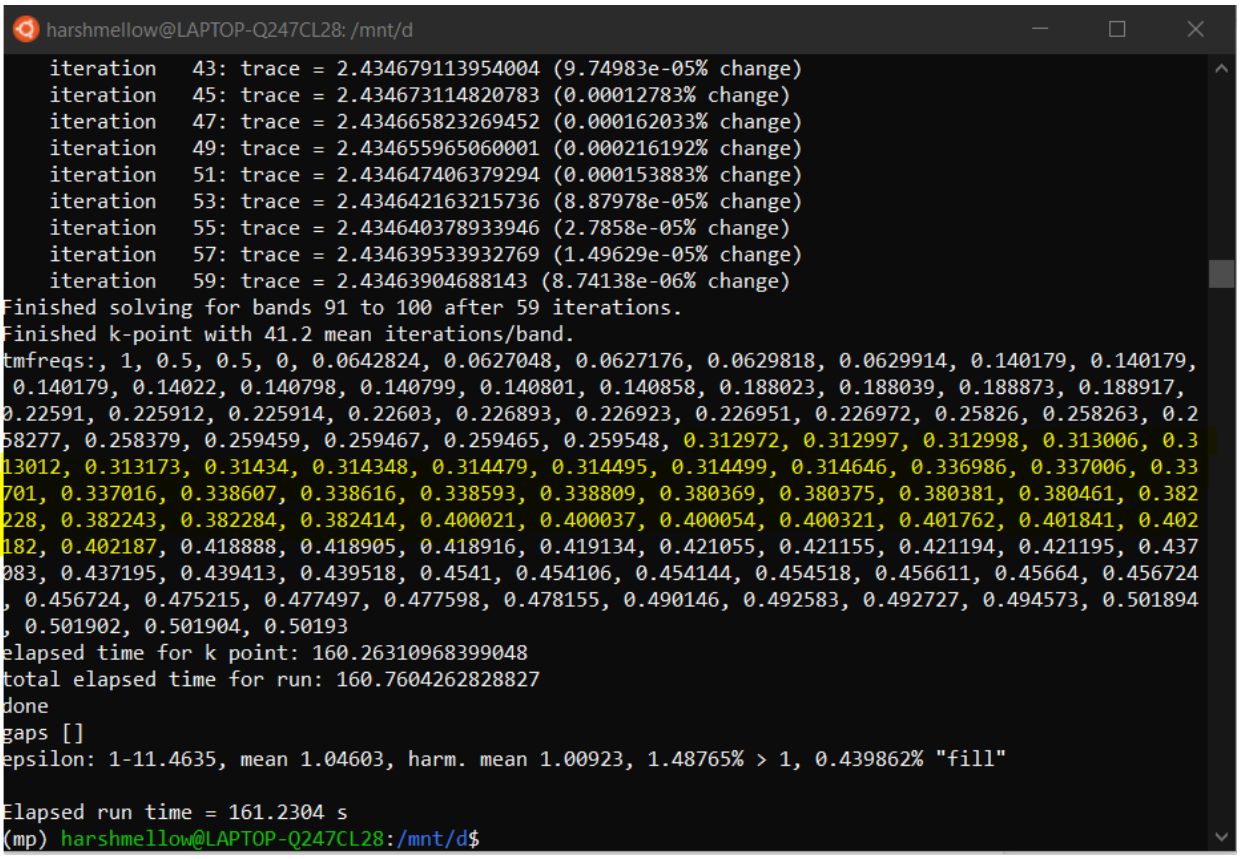
Observation -

The output clearly shows that there are new T.M. mode frequencies obtained within the band gaps. The band gaps were calculated before and the new frequencies are compared and highlighted. These defect modes lie within the band gap of 0.280947955 to 0.417114251086

Inference -

This is justifiable with the theory that if a line defect is created within the lattice then there should new frequencies obtained within the band gaps. This would mean that the light of 450 nm is able to propagate through the line defect and hence the working of the system is justified.

For 550 nm obtained TM freqs after creating line defect



Observation -

The output clearly shows that there are new T.M. mode frequencies obtained within the band gaps. The band gaps were calculated before and the new frequencies are compared and highlighted. These defect modes lie within the band gap of 0.280947955 to 0.417114251086. The change in design parameter included the change in ‘a’, the lattice constant and correspondingly the radius of the rods.

Inference -

This is justifiable with the theory that if a line defect is created within the lattice then there should new frequencies obtained within the band gaps. This would mean that the light of 550 nm is able to propagate through the line defect and hence the working of the system is justified.

Theory -

The gap between the first and second TM bands from $\omega a/2\pi c = 0.280947955$ to $\omega a/2\pi c = 0.417114251086$. Expressed as a fraction of the midgap frequency $\omega a/2\pi c = 0.3490305$.

If we want our operating wavelength $\lambda = 2\pi c/\omega = 4.5$ μm to lie at the middle of the gap, we need

$\omega a/2\pi c = a/\lambda = a/4.5$ μm $= 0.3490305$

$\Rightarrow a = 0.15706372$ μm.

Given the value of a, we calculate the rod radius $r = 0.2*a = 0.03141274$ μm, and the structure is completely determined.

Calculations supporting our system -

For 450 nm

The centre of the TM band gap from band 1 to band 2:

$$\frac{0.280947 + 0.417114}{2} = 0.3490305$$

Our operating frequency:

$$\lambda = 450\text{nm} = 0.45\mu\text{m}$$

Rescaling our structure in accordance with our operating frequency:

$$\Rightarrow \frac{\omega a}{2\pi c} = \frac{a}{\lambda} = \frac{a}{0.45\mu\text{m}} = 0.3490305$$

$$\Rightarrow a = 0.15706372$$

Also, the radius of rods: $0.2a$

$$= 0.2 \times 0.15706372$$

$$= 0.0314127\overline{4}$$

For 550 nm

The centre of the TM band gap from band 1 to band 2 :

$$\frac{0.280947 + 0.417114}{2} = 0.3490305$$

Our operating frequency :

$$\lambda = 550\,nm$$
$$= 0.55\,\mu m$$

Rescaling our structure in accordance with our operating frequency :

$$\Rightarrow \frac{\omega a}{2\pi c} = \frac{a}{\lambda} = \frac{a}{0.55\,\mu m} = 0.3490305$$

$$\Rightarrow a = 0.19196678$$

Also, the radius of rods : $0.2a$

$$= 0.2 \times 0.19196678$$
$$= 0.03839336$$

The choice of geometry Lattice

We have chosen the geometry lattice to be 20λ

Here we have taken $\lambda = 550\,nm$
$= 0.55\,\mu m$

$\Rightarrow$ our geometry lattice :

20×0.55

$\Rightarrow 11$

$\therefore$ geometry lattice : 11×11

References

https://mpb.readthedocs.io/
https://meep.readthedocs.io/en/latest/
http://ab-initio.mit.edu/book/photonic-crystals-book.pdf