Study the propagation of a laser beam in a wave-guide array

HAMZEH Abbas[1]

[1] *Lorraine University, Metz, France.*
[2] *CentraleSupélec, 2 Rue Edouard Belin, 57070 Metz, France.*

Abstract

A waveguide array is a set of regularly spaced waveguides that are close enough together for waveguide coupling to occur. The objective is to study beam propagation in the waveguide array under various conditions, including, for example, launching a beam into the central waveguide. The work is done in 1+1D in python language using the BPM method.

Keywords: waveguide, beam propagation, BPM.

1 Introduction

A waveguide in electromagnetism is an element capable of guiding an electromagnetic wave from an input point to an output point.Waveguides are encountered in many fields, as shown in the following list:

- In electromagnetism, waveguides are used to model electromagnetic guides, optical fibers, or optical microguides.
- In elasticity, waveguides allow to model pipes, or other cables, metallic bars present in industrial structures. As such, the study of these waveguides is essential for NDT (non-destructive testing), it is to test the soundness of a complex structure by sending waves and without destroying it.
- Finally, in acoustics, musical instruments or exhaust pipes can be modeled by waveguides. modeled by wave guides. We can also notice that a street can be seen as a particular case of waveguide. be seen as a particular case of waveguide.

The numerical study of the propagation of a wave in a guide is treated in our course, it is based by different numerical methods**[1]**: Transfer Matrix Method, Beam Propagation Method(BPM), Rigorous Coupled Wave Analysis and Finite Differences Time Domain(FDTD). For our project, we chose the numerical method BPM to study this propagation in a guide network formed by many guides made by SiO2 of refractive index n = 1.44 and a wavelength of = 1550nm. These parameters were chosen because they are best suited for propagation with less loss, less attenuation, and fewer nonlinear effects that affect the refractive index.

2 The guided propagation

The operating principle of a dielectric guide is based on the confinement of light in one (planar guide) or several directions (channel guides, optical fibers, etc.). A guiding zone (core) composed of a material of index n1, is surrounded by one or more non guiding zones (cladding) of index n2, n3 etc., lower than n1. When the optical wave is injected into the guiding zone, under certain conditions, it is trapped (confined) in the core until the exit of the structure.

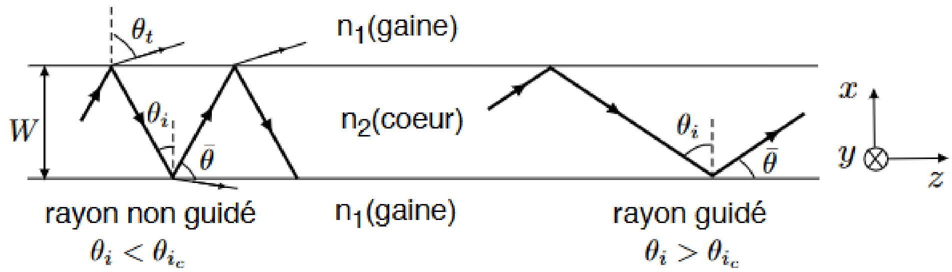

Figure 1. Schematic diagram of the optical confinement by total reflection in the case of the case of a symmetrical dielectric plane guide. All the rays having an angle θi > θic are guided.

These guides come in different shapes:

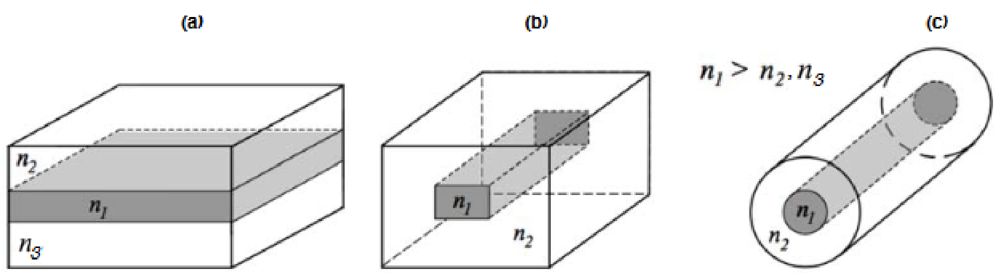

Figure 2. Different types of guides: flat guide (a), ribbon guide (b) and fiber optical fiber (c).

3 The optical coupling

When several guides are placed close enough, the wave injected in one of them can pass into the neighboring guides. This is the phenomenon of optical coupling. The first theoretical formalism developed by Yariv in 1973 **[2]** is the coupled mode theory (CMT) which is based on the coupling by evanescent waves. The theory of coupled modes has been the subject of numerous studies and its use is now being extended to the description of coupling phenomena in other domains than waveguides .

3.1 Optical coupling in a network of N guides

In this section, the theory of coupled modes is generalized to the case of a network composed of N guides, such as the one shown in figure 3 under the following conditions:

- all the guides composing the network must be identical (width, contrast index contrast ...),
- all guides are assumed to be single mode, only the TE0 mode can propagate,
- only the nearest neighbors are taken into account for the coupling. Thus only the n + 1 and n - 1 guides have an influence on the n guide.

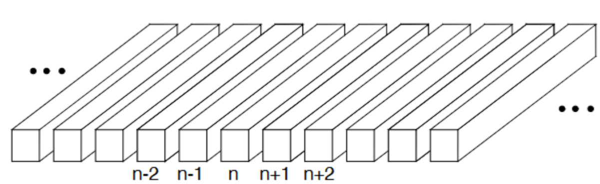

Figure 3. Schematic diagram of an array of identical waveguides.

3.2 Fields of application

Waveguides are used in many fields, from physics research, to electronics, to radar or optical tweezers used to move particles or biological objects such as cells, high power laser transmission, laser surgery, angioplasty, lithotripsy, near-field scanning Optical Microscopy Raman and IR Spectroscopy...**[3]**

4 BPM (Beam Propagation Method)

The BPM **[4]** is a numerical calculation method that is used to analyze optical structures, by modeling the propagation of a wave through a perturbation. This method consists in correcting the refractive index variations observed by an input beam that has propagated through a homogeneous space. The iteration step for the calculation is dz which divides the propagation into small portions and the evolution of the electric field in a portion is divided into three steps(figure:4):

- the first part seems to have a diffraction over a distance of $\frac{dz}{2}$ which is a linear part in a homogeneous space.
- the disruption is taken into account at $\frac{dz}{2}$.
- The third part is a repetition of the first part over the same length.

With the Fourier transforms, we can calculate, in the spectral domain, the propagation of a wave in a homogeneous medium. This is why the numerical method FFT (Fast Fourrier Transform) is used. Thus, we speak about FFT-BPM.

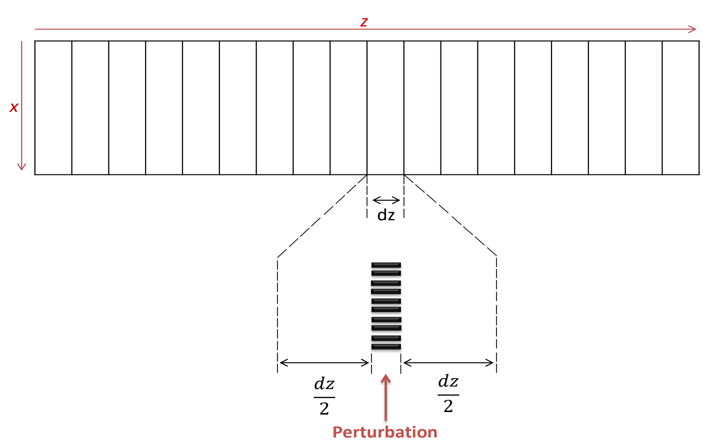

Figure 4. Diagram presenting the principle of the BPM method.

The calculation is summarized as follows(5): we consider an initial electric field E(z), by a Fourier transform following $x(TF_x)$ of E(z) we obtain the linear propagation over a distance $\frac{dz}{2}$ which takes the form:

$$E(z+\frac{dz}{2}) = E(z)\exp\left(\frac{i}{2k}(\frac{2\pi}{L})^2 n^2 \frac{dz}{2}\right), \tag{1}$$

where n is the index of undisturbed material. Then an inverse Fourier transform is applied to return to the spatial domain to apply the perturbation:

$$E^P(z+\frac{dz}{2}) = E(z+\frac{dz}{2})\exp -(ik(\frac{n}{n_0}-1)dz). \tag{2}$$

After, going back to the first step, a linear propagation on $\frac{dz}{2}$, we take the Fourrier transform, we get the following equation:

$$E(z+\Delta z) = E^{p}(z+\frac{dz}{2})\exp\left(\frac{i}{2k}(\frac{2\pi}{L})^{2}n^{2}\frac{dz}{2}\right) \tag{3}$$

Finally, we apply the last Reverse Fourrier Transform to have the electric field at the end of the dz portion.

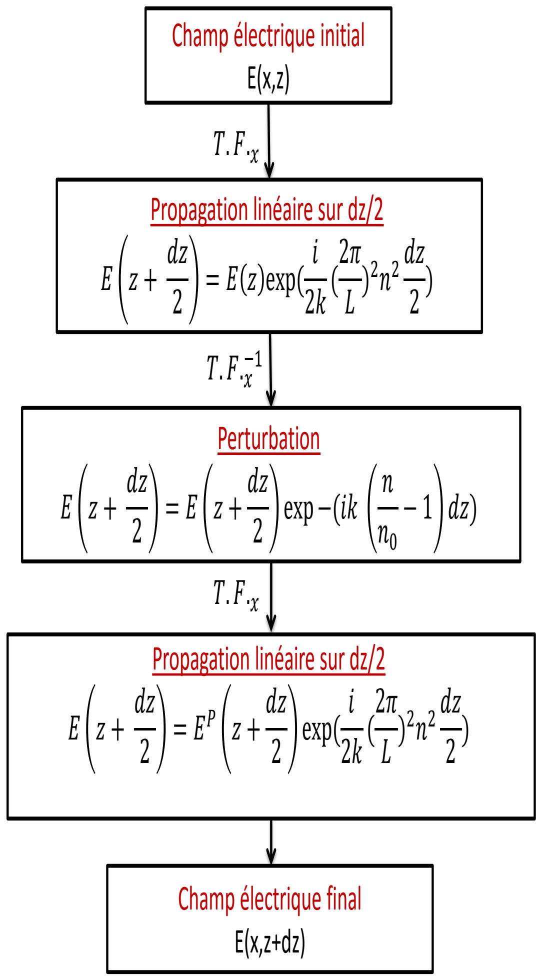

Figure 5. Algorithm of the BPM calculation method.

5 Similation and results

5.1 Python code

```
# -*- coding: utf-8 -*-
"""
Created on Sun Nov 13 16:13:02 2022

@author: El ve
"""

import numpy as np
from math import pi
import matplotlib.pyplot as plt
from matplotlib.backends.backend_pdf import PdfPages


class BPM():

    def __init__(self):

        self.tableau=None
        self.Lr=None
        self.dz=None
        self.l=None
        self.k=None
        self.Nb_etape=None
        self.i=complex(0,1)
        self.x=None
        self.y=None
        self.Y=None
        self.a=None
        self.b=None
        self.result=None

    def parametre(self,N,w0,largeur,lambd,n,n0,Min,Max,p,s,nb):

        self.N=N      #Nombre de points de la gaussienne
        self.w0=w0    #Largeur de la gaussienne
        self.largeur=largeur  #Largeur du guide
        self.lambd=lambd  #longueur d'onde
        self.n=n      #Indice de refraction du guide
        self.n0=n0    #Indice de refraction de l'eau
        self.Min=Min  #Bornes des guides
        self.Max=Max
        self.p=p
        self.s=s
        self.nb=nb
```

```
    def entree(self):        # faisceau initiale entrant

        self.a=-(self.N-1)/2
                                 # Centrage du nombre de points sur 0
        self.b=(self.N-1)/2


        self.x = np.linspace(self.a, self.b, self.N)*self.largeur/self.N
#Creation de l'axe des abscisses

        self.y = np.exp((-self.x**2)/(self.w0**2))        # Faisceau gaussien de depart


        self.Y=np.fft.fft(self.y)        # transformer de fourrier de la gaussienne



    def propagation(self):


         self.Lr = (pi*self.w0**2) / self.lambd        # Longueur de Rayleigh (dist pour


         self.dz = 0.001*self.Lr              # Distance de propagation

         self.k = 2*pi/self.lambd       # Vecteur d'onde

         self.l = np.linspace(self.a, self.b, self.N)



         self.exp1_dz =np.exp((self.i/(2*self.k))*((2*self.l*pi/self.largeur)**2)*self.d
#propagation lineaire dans  l espace  libre sur une distance  dz


         self.exp2_dz_2 =np.exp((self.i/(2*self.k))*((2*self.l*pi/self.largeur)**2)*(se
#propagation lineaire dans  l espace  libre sur une distance  dz/2



    def reseau(self):

         self.Nb_etape = self.nb

         lens = np.exp((-self.i*self.k*self.dz)*((self.n/self.n0)-1))    #creation de la
```

```
        self.tableau=np.ones(self.N,dtype=complex)
        for i in range (self.Min,self.Max,self.p):        #creation d'une r seau des g


            self.tableau[i:i+self.s]=lens


        self.result=np.zeros([self.N,self.nb],dtype=complex)

        self.result[:,0]= self.y    # premier colonne est la fonction gaussienne qui p



        self.y1= np.fft.fftshift([self.Y])   # decaler le graphique (centr )

    def sortie(self):

        for i in range(self.Nb_etape):

            self.y2=np.fft.ifft(self.y1)*self.tableau

            self.y1=np.fft.fft(self.y2)*self.exp1_dz

            self.result[:,i]=np.fft.ifft(self.y1)


    def plot(self):

        plt.plot (self.x , self.y,label="input")
        plt.plot (self.x ,( np.abs(self.result[: ,(self.Nb_etape- 1)] )) **2 ,label="ou
        plt.legend()
        plt.savefig('graphe.pdf')

        plt.show ()
        plt.show ()
        plt.imshow(abs(self.result),aspect='auto',cmap='jet')
        plt.colorbar()
        plt.savefig('faisseau.pdf')
```

```python
# -*- coding: utf-8 -*-
"""
Created on Sun Nov 13 19:11:29 2022

@author: El ve
"""

from BPM2 import *
f = BPM()
f.parametre(10001, 1.e-6, 100.e-6,1550.e-9,1.44,1.33,3400,6600,250,150,10000)
f.entree()
f.propagation()
f.reseau()
f.sortie()
f.plot()
```

5.2 Results

```
    from BPM2 import *
f = BPM()
f.parametre(10001, 1.e-6, 100.e-6,1550.e-9,1.44,1.33,3400,6600,250,150,10000)
f.entr e()
f.propagation()
f.r seau()
f.sortie()
f.plot()
```

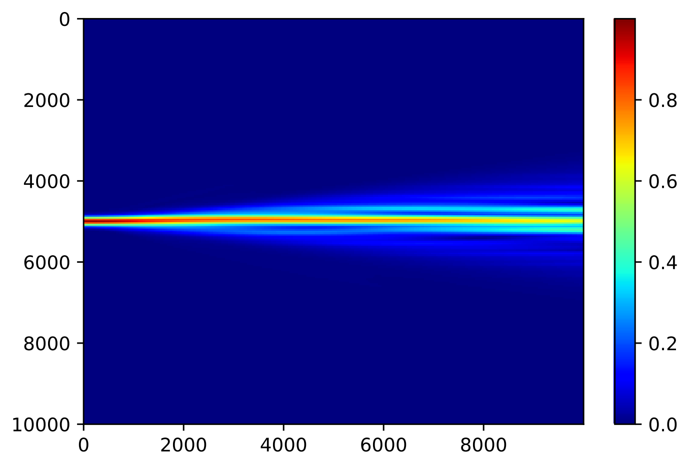

Figure 6. Beam propagation througth wave guide array.

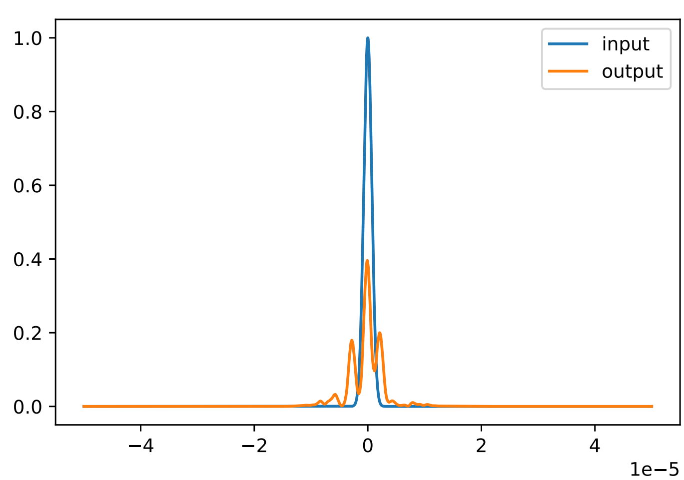

Figure 7. The normalized beam intensity for wave guide array

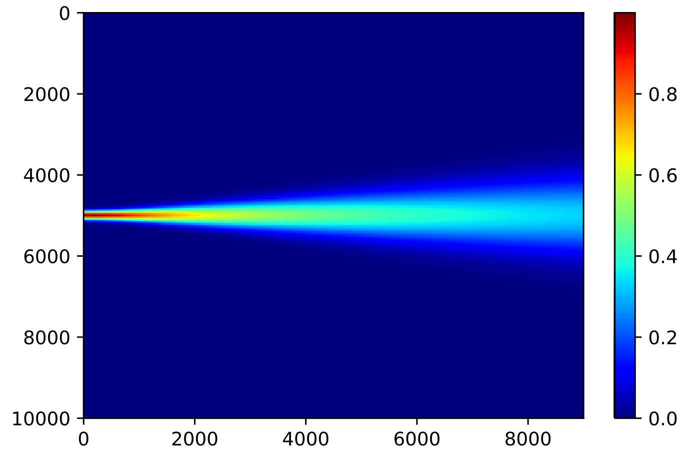

Figure 8. Beam propagation througth one guide.

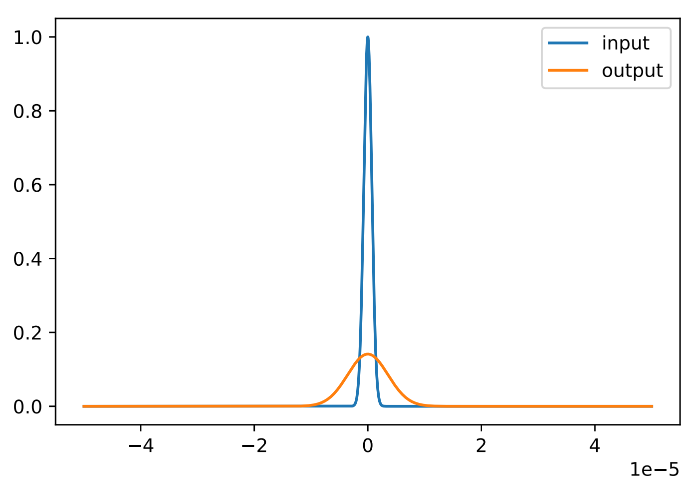

Figure 9. The normalized beam intensity for one guide.

Comparing figures 6,7 and 8,9 we notice that the output intensity for a single guide(<0.2) is much less than in an array of guides(0.4) (the parameters and dimensions are the same).

6 Conclusion

As we have seen in the previous sections, we can conclude that the use of a guide and even a network of guides leads to a decrease in intensity, but we can clearly reduce these losses of intensity while propagating in a network of guides instead of a single guide, moreover we can still regularize these losses for example by changing the parameters or by changing the dimensions of the guides.

References

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