Capacitação em fotônica

MMI – Multi mode interferometer

Adolfo Herbster

Part 1

Fundamental properties of vector modes

- Complete basis for the decomposition of the fields **E** and **H**:

$$\mathbf{E} = \sum_j \mathbf{E}_j + \mathbf{E}_{-j} + \mathbf{E}_{rad} \tag{1}$$

$$\mathbf{H} = \sum_j \mathbf{H}_j + \mathbf{H}_{-j} + \mathbf{H}_{rad} \tag{2}$$

$$\mathbf{E}_j\left(x, y, z\right) = \mathbf{e}_j\left(x, y\right)\, e^{i\beta_j z} = \left(\mathbf{e}_{tj} + \hat{\mathbf{z}} e_{zj}\right) e^{i\beta_j z} \tag{3}$$

$$\mathbf{H}_j\left(x, y, z\right) = \mathbf{h}_j\left(x, y\right)\, e^{i\beta_j z} = \left(\mathbf{h}_{tj} + \hat{\mathbf{z}} h_{zj}\right) e^{i\beta_j z} \tag{4}$$

Propagation constant and phase velocity

- The *j*-th eigenvalue solution of the wave equation:

$$\beta_j = \frac{\frac{k}{2}\int_{A_\infty}\left[\sqrt{\frac{\mu_0}{\varepsilon_0}}\mathbf{h}_j^2 + \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(n^2\right)^*\mathbf{e}_j^2\right]\mathrm{d}A}{\int_{A_\infty}\mathbf{e}_j \times \mathbf{h}_j \cdot \hat{\mathbf{z}}\,\mathrm{d}A} \qquad (1)$$

- Each mode propagates with a phase velocity

$$v_{pj} = \frac{\omega}{\beta_j} \qquad (1)$$

Orthonormality of guided modes

- The general orthonormality relation of the forward and backward-propagating guided modes is

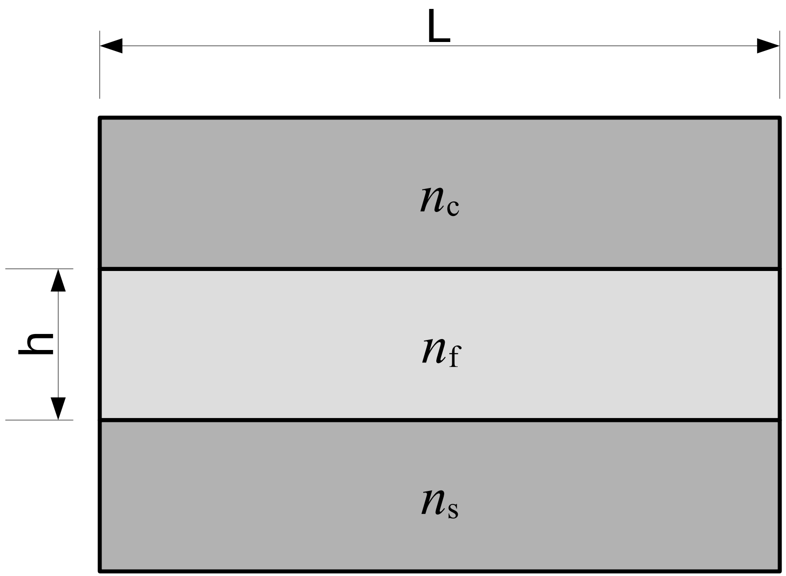
$$\frac{1}{2}\int_{A_\infty} \hat{\mathbf{e}}_j \times \hat{\mathbf{h}}_k^* \cdot \hat{\mathbf{z}}\,\mathrm{d}A = \begin{cases} 1 \text{ if } j = k, \\ 0 \text{ if } j \neq k. \end{cases}$$

- where

$$\hat{\mathbf{e}}_j = \frac{\mathbf{e}_j}{\sqrt{N_j}},\ \hat{\mathbf{h}}_j = \frac{\mathbf{h}_j}{\sqrt{N_j}} \text{ and } N_j = \tfrac{1}{2}\left|\int_{A_\infty} \mathbf{e}_j \times \mathbf{h}_j^* \cdot \hat{\mathbf{z}}\,\mathrm{d}A\right|$$

Orthonormality of guided modes

- Considering a symmetric dieletric waveguide:



TE modes

$$H_z, E_y, H_x$$

$$\nabla_T^2 H_z + k_c^2 H_z = 0$$

$$\mathbf{H}_T = -j\frac{\beta}{k_c^2}\nabla_T H_z$$

$$\mathbf{E}_T = \eta_{\mathrm{TE}}\,\mathbf{H}_T \times \hat{\mathbf{z}}.$$

TM modes

$$E_z, H_y, E_x$$

$$\nabla_T^2 E_z + k_c^2 E_z = 0$$

$$\mathbf{E}_T = -j\frac{\beta}{k_c^2}\nabla_T E_z$$

$$\mathbf{H}_T = \frac{1}{\eta_{\mathrm{TM}}}\,\hat{\mathbf{z}} \times \mathbf{E}_T.$$

Show the orthonormality of guided modes in this device.

Poynting vector and power density

- The general definition of the Poyting vector is

$$\mathbf{S} = \frac{1}{2}\mathcal{R}\left(\mathbf{E} \times \mathbf{H}^*\right)$$

- The power density o *j*-th mode is

$$S_{jz} = \mathbf{S}_j \cdot \hat{\mathbf{z}} = \frac{1}{2}\left|a_j\right|^2 \hat{\mathbf{e}}_j \times \hat{\mathbf{h}}_j^* \cdot \hat{\mathbf{z}},\ \mathbf{e}_j = a_j \hat{\mathbf{e}}_j \text{ and } \mathbf{h}_j = a_j \hat{\mathbf{h}}_j$$

- The power carried by the mode *j* is given by the integration of

$$P_j = \frac{1}{2}\left|a_j\right|^2 \int_{A_\infty} \hat{\mathbf{e}}_j \times \hat{\mathbf{h}}_j^* \cdot \hat{\mathbf{z}}\, \mathrm{d}A = \left|a_j\right|^2$$

Poynting vector and power density

- The total power carried by all guided and radiated modes is

$$P_{tot} = \underbrace{P_{gd}}_{\text{guided}} + \underbrace{P_{rad}}_{\text{radiated}}$$

- $$P_{gd} = \sum_j (P_j + P_{-j}) = \sum_j |a_j|^2 - \sum_j |a_{-j}|^2$$

Expansion of the fields onto the basis of guided modes

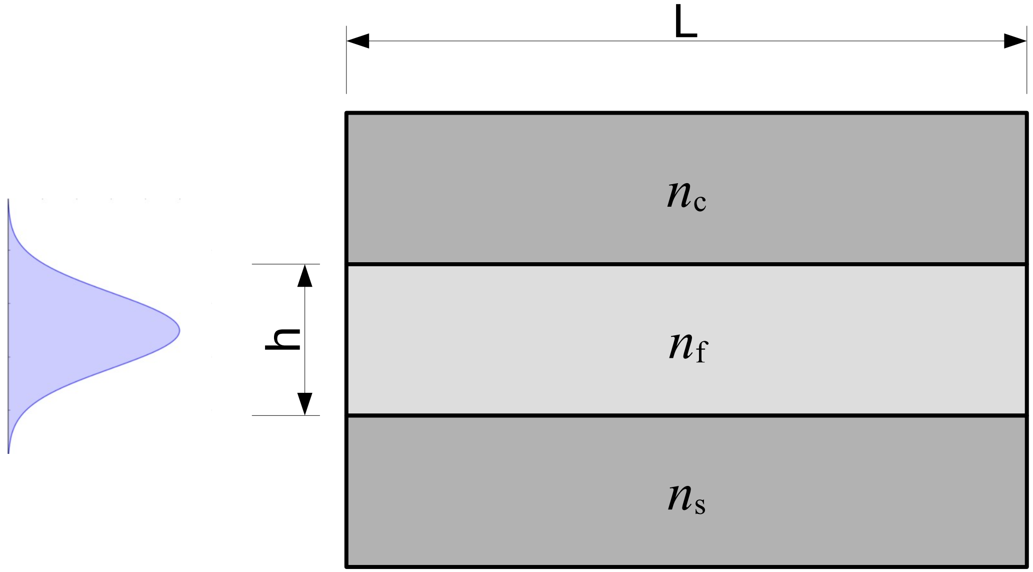
- Far from the excitation sources and waveguides perturbations;
- The guided fields can be decomposed on the finite orthonormal basis of forward and backward-propagating guied modes:

$$\mathbf{E} = \sum_j a_j \hat{\mathbf{e}}_j + a_{-j} \hat{\mathbf{e}}_{-j} \rightarrow a_j = \frac{1}{2} \int_{A_\infty} \mathbf{E} \times \hat{\mathbf{h}}_j^* \cdot \hat{\mathbf{z}} \, \mathrm{d}A$$

$$\mathbf{H} = \sum_j a_j \hat{\mathbf{h}}_j + a_{-j} \hat{\mathbf{h}}_{-j} \rightarrow a_{-j} = -\frac{1}{2} \int_{A_\infty} \mathbf{E} \times \hat{\mathbf{h}}_{-j}^* \cdot \hat{\mathbf{z}} \, \mathrm{d}A$$

Expansion of the fields

- Suppose that a Gaussian pulse is incident on a slab waveguide;
- A number of supported modes will be excited and propagated in the core region;



Expansion of the fields

- Consider a slab waveguide with width of 1 um and n_s = 1.52, n_f = 1.674 and n_c = 1.0. The structure supports 2 modes at wavelength of 633 nm. Calculate the transmission of the **TE mode** at L = 633 nm.

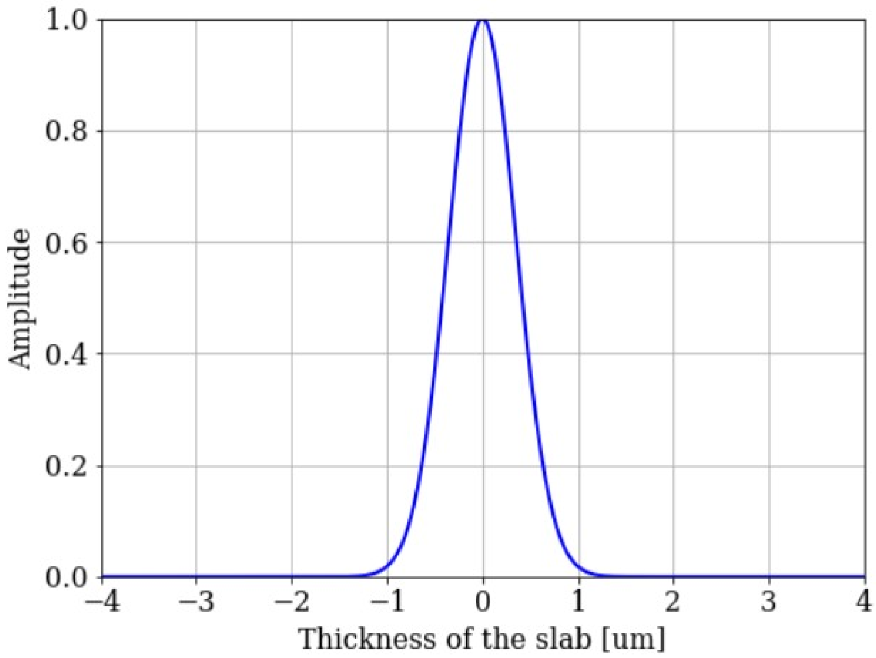
1) Calculate the field profile and propagation constant of each mode;
2) Check the orthogonality and adjust the amplitude;
3) Generate the Gaussian input pulse;
4) Calculate the amplitude of the propagated pulse and generate the propagated output pulse;
5) Calculate the transmission;

Input signal – Gaussian pulse

$$\Psi\left(y\right) = e^{\left(\frac{y}{\omega_0}\right)^2}$$

```
w_0 = W_m/2
phi_in = np.exp(-(x/w_0)**2)
```

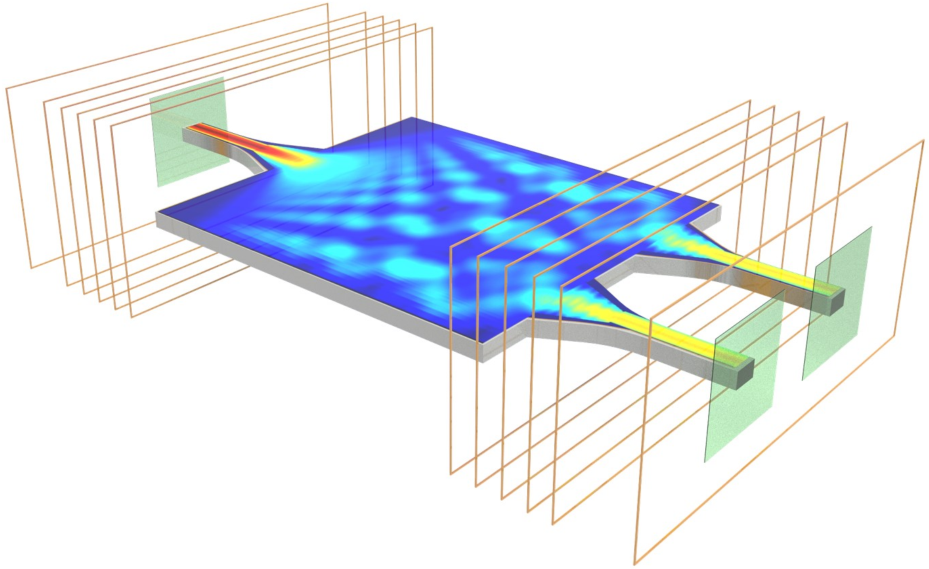
```
plt.figure(figsize=(8,6))
plt.plot(1e6*x, phi_in, linewidth = 2)
plt.grid(True)
plt.xlabel('Thickness of the slab [um]')
plt.ylabel('Amplitude')
plt.xlim([-4,4])
plt.ylim([0,1])
```



Part 2

Multi-mode interference device

- The operation of optical MMI devices is based on the self-imaging principle;
- **Self-imaging is a property of multimode waveguides by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide**;



Multimode interference (MMI) coupler – Font: www.lumerical.com

Multi-mode interference device

- The operation of optical MMI devices is based on the self-imaging principle;
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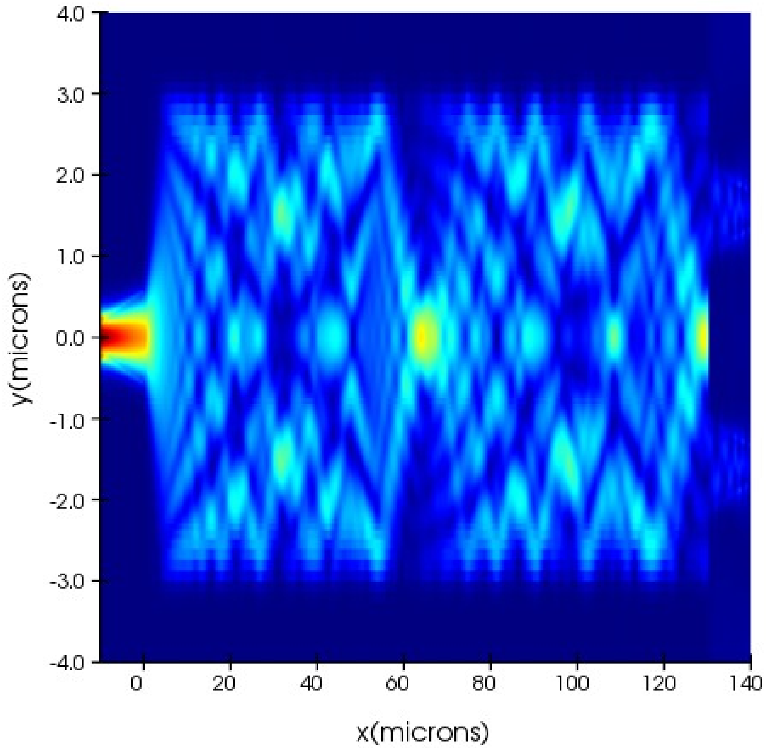


Multimode interference (MMI) coupler – simulated using Lumerical MODE.

Device

- Step-index multimode waveguide;
- Width W_M, refractive index n_r and cladding refractive index n_c;

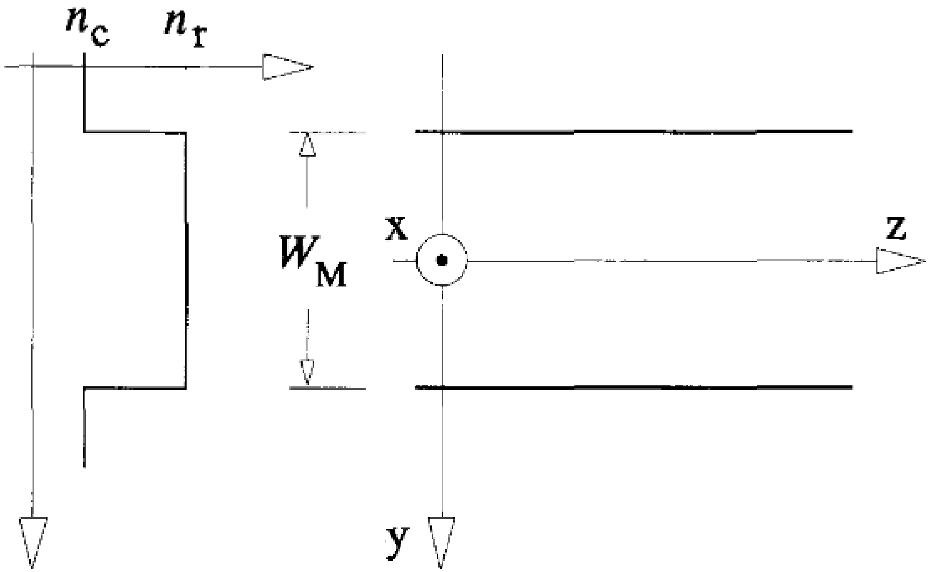


Fig. 1. Two-dimensional representation of a step-index multimode waveguide; (effective) index lateral profile (left), and top view of ridge boundaries and coordinate system (right).

Device

- Step-index multimode waveguide;
- Width W_M, refractive index n_r and cladding refractive index n_c;
- Supports m lateral modes $\upsilon = 0, 1, \ldots, (m\text{-}1)$ at free-space wavelength λ_0;
- The wavenumber k_c and the propagation constant β_υ are related with

$$k_c^2 + \beta_\nu^2 = k_0^2 n_r^2,\ k_0 = \frac{2\pi}{\lambda_0},\ k_c = \frac{(\nu+1)\pi}{W_{e\nu}}$$

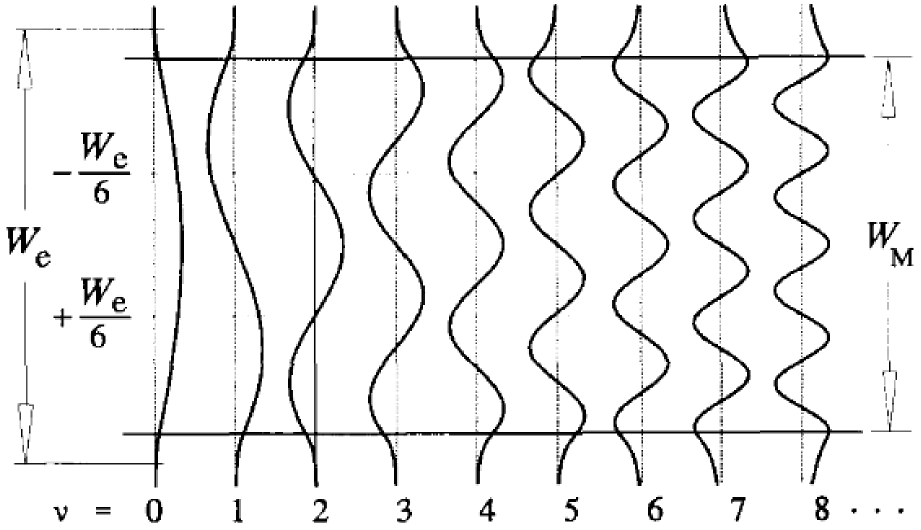


Fig. 2. Example of amplitude-normalized lateral field profiles $\psi_\nu(y)$, corresponding to the first 9 guided modes in a step-index multimode waveguide.

$$W_{e\nu} \simeq W_e = W_M + \left(\frac{\lambda_0}{\pi}\right)\left(\frac{n_c}{n_r}\right)^{2\sigma}\left(n_r^2 - n_c^2\right)^{-\frac{1}{2}}$$

More details about $W_{e\nu}$, see Lucas & Erik [1].

Device

```python
n_c = 1.5
n_r = 3.5
lambda_0 = 1550e-9
k_0 = 2*np.pi/lambda_0
W_m = 1e-6
c0  = 299792458
```

```python
sigma = 0 #TE mode
We = W_m + (lambda_0/np.pi)*((n_c/n_r)**(2*sigma))*(n_r**2 - n_c**2)**(-0.5)
```

```python
for i in range(5):
    neff_app = n_r - ((i+1)**2 * np.pi * lambda_0)/(We**2*4*n_r*k_0)
    k_c = (i + 1)*np.pi/We
    print("neff_app = %4.3f" %(neff_app))
```

```
neff_app = 3.436
neff_app = 3.243
neff_app = 2.922
neff_app = 2.473
neff_app = 1.895
```

$$\beta_\nu \simeq k_0 n_r - \frac{(\nu+1)^2 \pi \lambda_0}{4 n_r W_e^2}, \quad \text{if } k_c^2 \ll (k_0 n_r)^2$$

Rohan D. Kekatpure, Aaron C. Hryciw, Edward S. Barnard, and Mark L. Brongersma, "Solving dielectric and plasmonic waveguide dispersion relations on a pocket calculator," Opt. Express 17 (2009)

TE	beta	neff	kf	als	alc
0	1.391856e+07	3.433571	2.751090e+06	1.252013e+07	1.252013e+07
1	1.310526e+07	3.232939	5.435704e+06	1.160928e+07	1.160928e+07
2	1.166455e+07	2.877530	8.076693e+06	9.954359e+06	9.954359e+06
3	9.409787e+06	2.321302	1.061841e+07	7.181337e+06	7.181337e+06
4	6.204527e+06	1.530596	1.275926e+07	1.234361e+06	1.234361e+06

Device

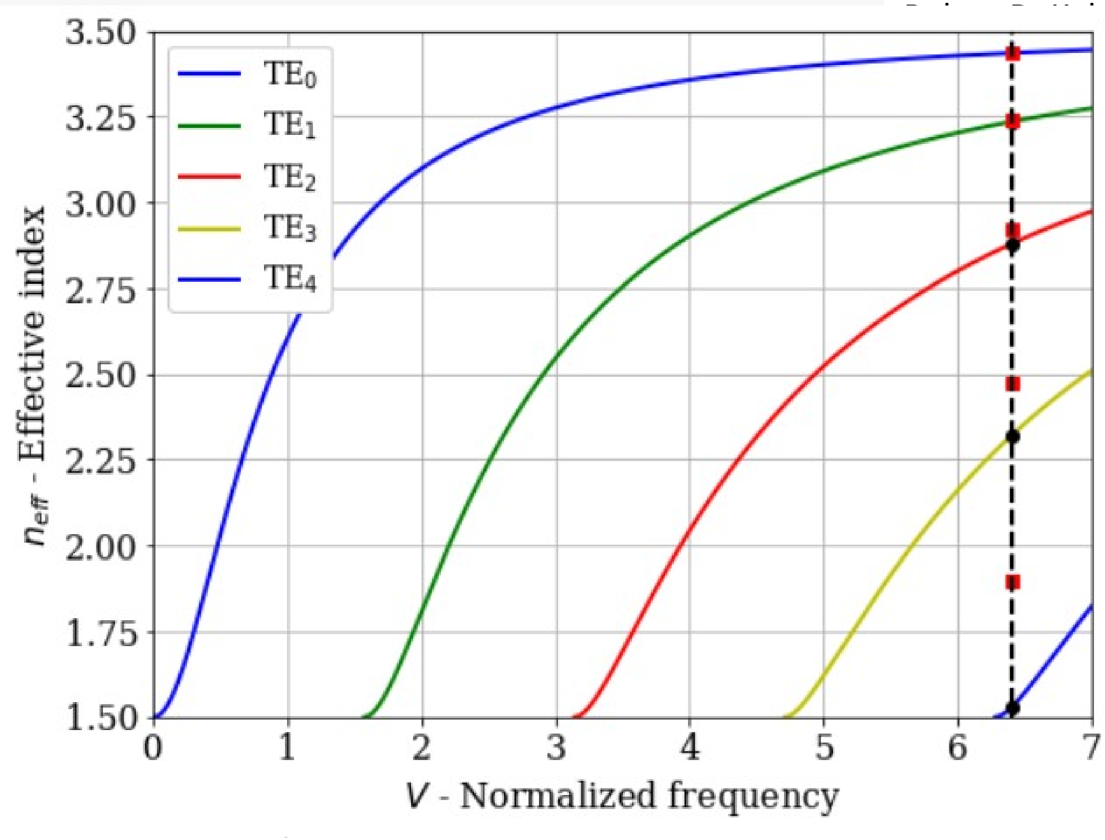
```
n_c = 1.5
n_r = 3.5
lambda_0 = 1550e-9
k_0 = 2*np.pi/lamb
W_m = 1e-6
c0  = 299792458
```

```
sigma = 0 #TE mode
We = W_m + (lambda
```

```
for i in range(5):
    neff_app = n_r
    k_c = (i + 1)*
    print("neff_ap
```

```
neff_app = 3.436
neff_app = 3.243
neff_app = 2.922
neff_app = 2.473
neff_app = 1.895
```

$\beta_\nu \simeq k_0 n_r$



tpure, Aaron C. Hryciw, Edward S. Barnard,
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veguide dispersion relations on a pocket
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neff	kf	als	alc
3.433571	2.751090e+06	1.252013e+07	1.252013e+07
3.232939	5.435704e+06	1.160928e+07	1.160928e+07
2.877530	8.076693e+06	9.954359e+06	9.954359e+06
2.321302	1.061841e+07	7.181337e+06	7.181337e+06
1.530596	1.275926e+07	1.234361e+06	1.234361e+06

Device

```python
n_c = 1.5
n_r = 3.5
lambda_0 = 1550e-9
k_0 = 2*np.pi/lambda_0
W_m = 5e-6
c0  = 299792458
```

```python
sigma = 0 #TE mode
We = W_m + (lambda_0/np.pi)*((n_c/n_r)**(2*sigma))*(n_r**2 - n_c**2)**(-0.5)
```

```python
for i in range(5):
    neff_app = n_r - ((i+1)**2 * np.pi * lambda_0)/(We**2*4*n_r*k_0)
    k_c = (i + 1)*np.pi/We
    print("neff_app = %4.3f" %(neff_app))
```

```
neff_app = 3.497
neff_app = 3.487
neff_app = 3.471
neff_app = 3.448
neff_app = 3.419
```

Rohan D. Kekatpure, Aaron C. Hryciw, Edward S. Barnard, and Mark L. Brongersma, "Solving dielectric and plasmonic waveguide dispersion relations on a pocket calculator," Opt. Express 17 (2009)

TE	beta	neff	kf	als	alc
0	1.417475e+07	3.496771	6.092989e+05	1.280433e+07	1.280433e+07
1	1.413541e+07	3.487067	1.218556e+06	1.276077e+07	1.276077e+07
2	1.406962e+07	3.470836	1.827728e+06	1.268785e+07	1.268785e+07
3	1.397701e+07	3.447992	2.436771e+06	1.258509e+07	1.258509e+07
4	1.385709e+07	3.418407	3.045639e+06	1.245176e+07	1.245176e+07
5	1.370916e+07	3.381914	3.654279e+06	1.228692e+07	1.228692e+07
6	1.353236e+07	3.338299	4.262636e+06	1.208934e+07	1.208934e+07
7	1.332560e+07	3.287294	4.870647e+06	1.185745e+07	1.185745e+07
8	1.308754e+07	3.228567	5.478239e+06	1.158927e+07	1.158927e+07
9	1.281653e+07	3.161713	6.085328e+06	1.128233e+07	1.128233e+07
10	1.251057e+07	3.086235	6.691812e+06	1.093352e+07	1.093352e+07

Input signal

- A input field profile imposed at $z = 0$ and totally contained within W_e will be decomposed into the modal field distributions of all modes (including guided as well as radiative modes):

$$\underbrace{\Psi\left(y,0\right)}_{\text{input field}} = \sum_{\nu} c_{v} \underbrace{\psi_{\nu}\left(y\right)}_{\text{modal field}} \rightarrow \Psi\left(y,0\right) = \sum_{\nu=0}^{m-1} c_{v}\psi_{\nu}\left(y\right)$$

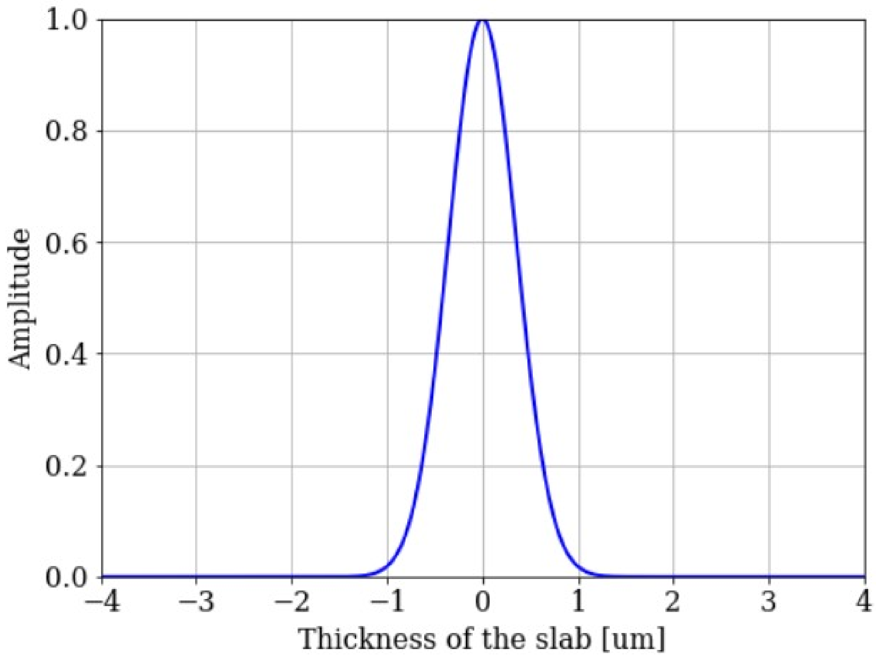
$$c_{\nu} = \int \Psi\left(y,0\right)\psi_{\nu}\left(y\right)\, dy$$

Input signal – example: gaussian pulse

$$\Psi\left(y,0\right) = e^{\left(\frac{y}{\omega_0}\right)^2}$$

```
w_0 = W_m/2
phi_in = np.exp(-(x/w_0)**2)
```

```
plt.figure(figsize=(8,6))
plt.plot(1e6*x, phi_in, linewidth = 2)
plt.grid(True)
plt.xlabel('Thickness of the slab [um]')
plt.ylabel('Amplitude')
plt.xlim([-4,4])
plt.ylim([0,1])
```



Field profile

- The field profile at z can be written as a superposition

$$\Psi(y,z) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) \exp\left[j\left(\omega t - \beta_\nu z\right)\right]$$

$$= \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) \exp\left[j\left(\beta_0 - \beta_\nu\right) z\right]$$

Taking the phase of the fundamental mode as a common factor out of the sum, dropping it and assuming the time dependence $\exp(jwt)$ implicit hereafter.

$$\Psi(y,L) = \sum_{\nu=0}^{m-1} \boxed{c_\nu} \psi_\nu(y) \boxed{\exp\left[j\frac{\nu(\nu+2)\pi}{3L_\pi} L\right]}$$

$\mathbf{z = L}$

All depends on the modal excitation c_ν and the properties of the mode phase factor.

Field profile

- The field profile at z can be written as a superposition

$$\Psi(y,z)=\sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y)\exp\left[j\left(\omega t-\beta_\nu z\right)\right]$$

$$=\sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y)\exp\left[j\left(\beta_0-\beta_\nu\right)z\right]$$

$$\Psi(y,L)=\sum_{\nu=0}^{m-1} \boxed{c_\nu}\psi_\nu(y)\boxed{\exp\left[j\frac{\nu(\nu+2)\pi}{3L_\pi}L\right]}$$

$$\nu(\nu+2)=\begin{cases}\text{even for } \nu \text{ even}\\ \text{odd for } \nu \text{ odd}\end{cases}$$

$$\psi_\nu(-y)=\begin{cases}\psi_\nu(y) & \text{for } \nu \text{ even}\\ -\psi_\nu(y) & \text{for } \nu \text{ odd}\end{cases}$$

properties

Types of interference

- General interference: independent of the modal excitation (all modes):
  - Single images;
  - Multiples images;
- Restricted interference: obtained by exciting certain modes alone:
  - Paired interference;
  - Symmetric interference;

Types of interference

General interference

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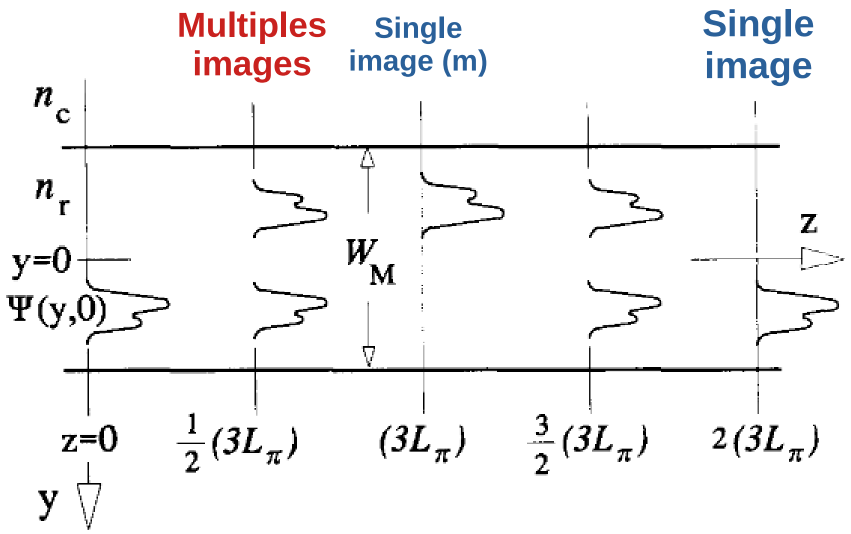


Fig. 3. Multimode waveguide showing the input field $\Psi(y,0)$, a mirrored single image at $(3L_\pi)$, a direct single image at $2(3L_\pi)$, and two-fold images at $\frac{1}{2}(3L_\pi)$ and $\frac{3}{2}(3L_\pi)$.

Types of interference

General interference

- General interference: independent of the modal excitation (all modes):
  - Single images;

$$\exp\left[j\frac{\nu(\nu+2)\pi}{3L_\pi}L\right] = 1 \text{ or } (-1)^\nu$$

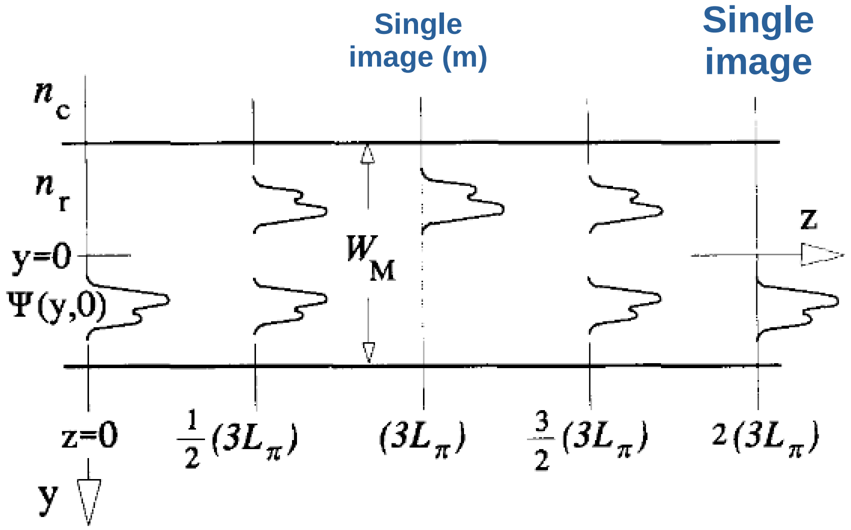
Phase changes of all modes must differ by integer multiples of 2π

Phase changes must be alternatively even and odd multiples of π (mirrored)

- Solution:

$$L = p\,(3L_\pi) \quad \text{with } p = 0, 1, 2, \ldots$$

  - For p even (single image) and p odd (single image mirrored);



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Types of interference

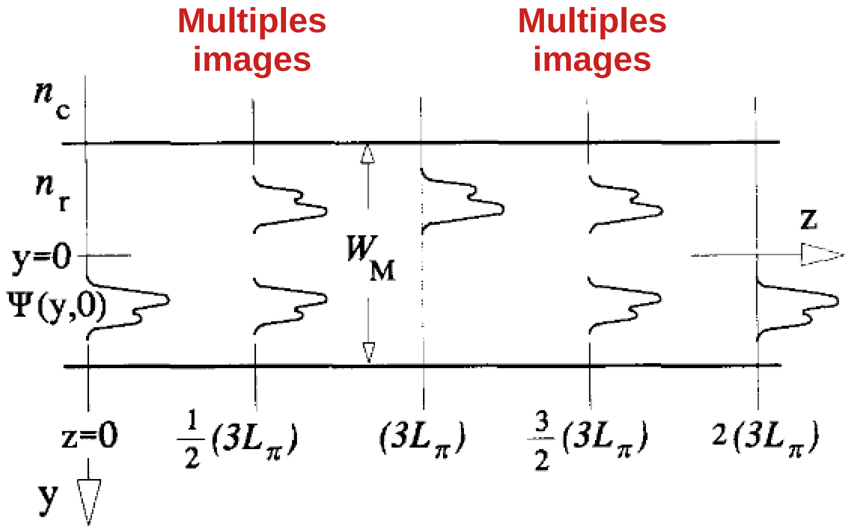
General interference

- General interference: independent of the modal excitation (all modes):
  - Multiples images;
- Consider that (why not even p?)

$$L = \frac{p}{2}\left(3L_\pi\right) \quad \text{with } p = 1, 3, 5, \ldots$$

- The total field at these lengths is

$$\Psi\left(y, \frac{p}{2}3L_\pi\right) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) \exp\left[j\nu(\nu+2)p\left(\frac{\pi}{2}\right)L\right]$$
$$= \sum_{\nu \text{ even}} c_\nu \psi_\nu(y) + \sum_{\nu \text{ odd}} (-j)^p c_\nu \psi_\nu(y)$$
$$= \frac{1+(-j)^p}{2}\Psi(y,0) + \frac{1-(-j)^p}{2}\Psi(-y,0)$$



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Types of interference

General interference

- In general, at

$$L = \frac{p}{N}\left(3L_\pi\right),\ p \geq 0 \text{ and } N \geq 0 \text{ (integers with no common divisor)}$$

- The field will be

$$\Psi\left(y,L\right) = \frac{1}{C}\sum_{q=0}^{N-1}\Psi_{in}(y-y_q)\exp\left(j\varphi_q\right) \text{ with } y_q = p\left(2q-N\right)\frac{W_e}{N} \text{ and } \varphi_q = p\left(N-q\right)q\left(\frac{\pi}{N}\right)$$

- Where C is a complex normalization constant ($|C| = \sqrt{N}$), p indicates the imaging periodicity along z, and q refers to each of the N images along y;
- The above equations show that: at distances $z = L$, N images are formed of the extended field $\Psi_{\mathrm{in}}\left(y\right)$, located at the positions y_q, each wih amplitude $1/\sqrt{N}$ and phase φ_q ($p = 1$ – shortest devices).
- For example, $N = 2$ and $p = 1$;

Types of interference

General interference

- In general, at

$L = \frac{p}{N}(3L_\pi)\,,\; p \geq$ divisor)

- The field will be

$\Psi(y, L) = \frac{1}{C}\sum_{q=0}^{N-1} \Psi_{in}($ $= p(N-q)\,q\left(\frac{\pi}{N}\right)$

- Where C is a com p indicates the imaging periodicit mages along y;

- The above equati ges are formed of the extended field wih amplitude $1/\sqrt{N}$ and phase

- For example, $N =$

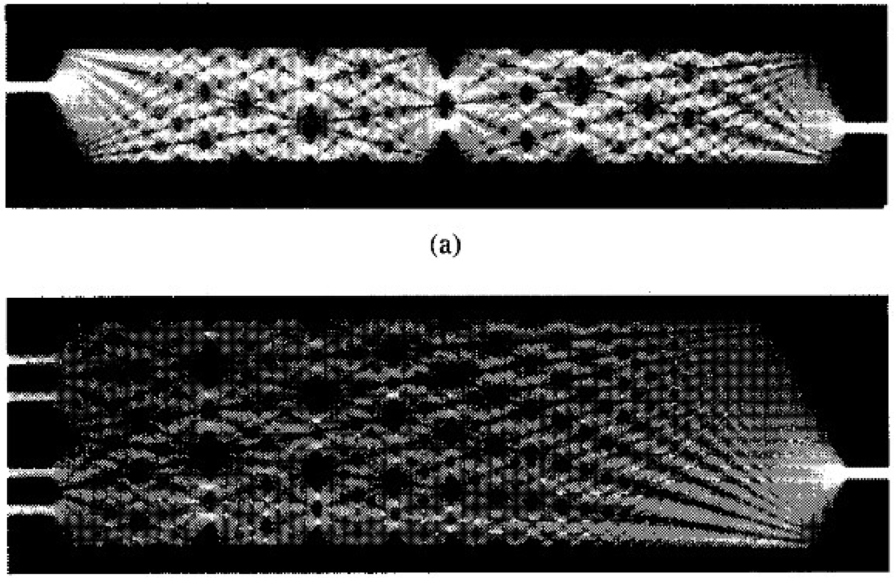


Fig. 5. Theoretical light intensity patterns corresponding to general or paired interference mechanisms in two multimode waveguides, leading to a mirrored single image (a), and a 4-fold image (b). Note also the multi-fold images at intermediate distances, non-equally spaced along the lateral axis. Reproduced by kind permission of J. M. Heaton, ©British Crown Copyright DRA 1992.

Types of interference

- General interference: independent of the modal excitation (all modes):
  - Single images;
  - Multiples images;
- Restricted interference: obtained by exciting certain modes alone:
  - **Paired interference;**
  - Symmetric interference;

Types of interference

Restricted interference - paired

- Only some guided modes in the multimode waveguide are excited by the input fields;
- By lauching an even symmetric input field $\Psi(y,0)$ (e.g. a Gaussian beam) at $y = \pm W_e$, the modes $\upsilon = 2$, 5, 8, … present a zero with odd symmetry and $c_\upsilon = 0$;
- By the same token, two-fold images are

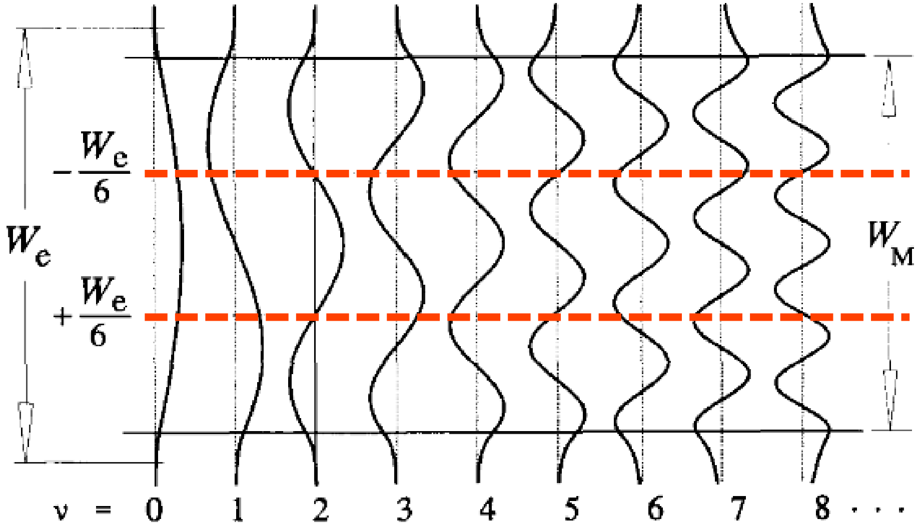


Fig. 2. Example of amplitude-normalized lateral field profiles $\psi_\nu(y)$, corresponding to the first 9 guided modes in a step-index multimode waveguide.

$$L = p\,(L_\pi) \quad \text{with } p = 0, 1, 2, \ldots \quad \text{(single imagens - direct and inverted)}$$

$$L = \frac{p}{N}\,(L_\pi) \quad \text{with } p = 0, 1, 2, \ldots \quad (N\text{-fold images where } p \geq 0 \text{ and } N \geq 0)$$

Types of interference

- General interference: independent of the modal excitation (all modes):
  - Single images;
  - Multiples images;
- Restricted interference: obtained by exciting certain modes alone:
  - Paired interference;
  - **Symmetric interference;**

Types of interference

Restricted interference - symmetric

- Exciting only the even symmetric modes;
- For the modes $\upsilon = 1, 3, 5, \ldots, c_\upsilon = 0$;
- $1\mathrm{x}N$ beam splitters can be realized with multimode waveguides four times shorter;
- In general, N-fold images are obtained at distances

$$L = \frac{p}{N}\left(\frac{3L_\pi}{4}\right)$$

with N images of the input field, symmetrically located along the y-axis with equal spaceings W_e/N.

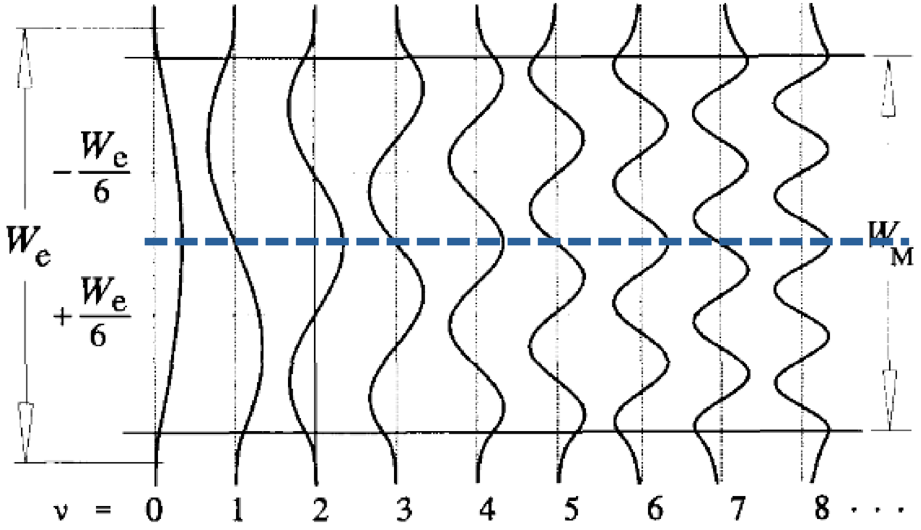


Fig. 2. Example of amplitude-normalized lateral field profiles $\psi_\nu(y)$, corresponding to the first 9 guided modes in a step-index multimode waveguide.

Types of interference

Restricted interference - symmetric

- Exciting only the e
  modes;
- For the modes $\upsilon = 1, 3$
- $1\mathrm{x}N$ beam splitters
  with multimode waveg
  shorter;
- In general, N-fold ima
  at distances

$$L = \frac{p}{N}\left(\frac{3L_\pi}{4}\right)$$

with N images of
symmetrically located
with equal spaceings

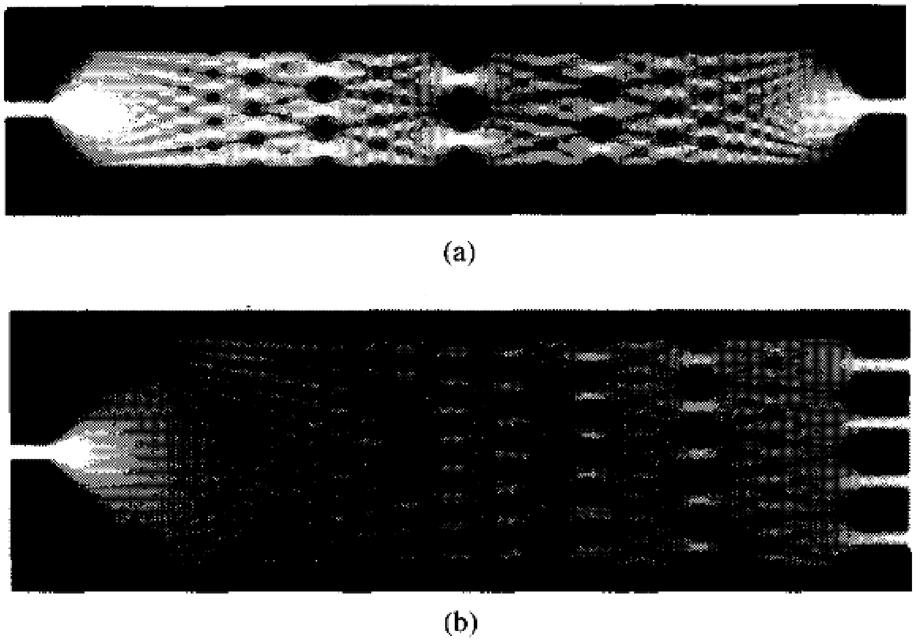
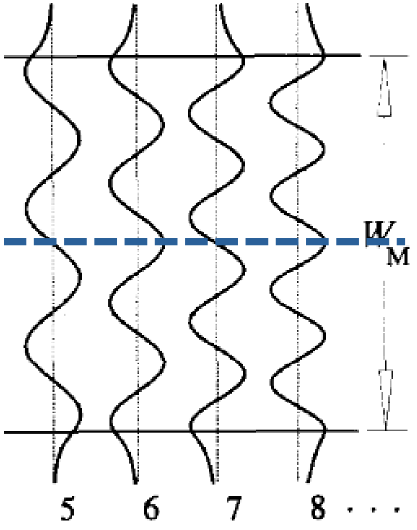


Fig. 7. Theoretical light intensity patterns corresponding to (single-input) symmetric interference mechanisms in a 20-μm-wide multimode waveguide, showing "1 × 1" imaging (a); and in a 40-μm-wide multimode waveguide, showing 1-to-4 way splitting (b). Note also the multi-fold images at intermediate distances, equally spaced along the lateral axis. Reproduced by kind permission of J. M. Heaton *et al.* [34]. ©British Crown Copyright DRA 1992.



d lateral field profiles $\psi_\nu(y)$, cor-
a step-index multimode waveguide.

Types of interference

- General interference: independent of the modal excitation (all modes):
  - Single images;
  - Multiples images;
- Restricted interference: obtained by exciting certain modes alone:
  - Paired interference;
  - Symmetric interference;

TABLE I

SUMMARY OF CHARACTERISTICS OF THE GENERAL, PAIRED, AND SYMMETRIC INTERFERENCE MECHANSIMS

Interference mechanism	*General*	*Paired*	*Symmetric*
Inputs × Outputs	$N \times N$	$2 \times N$	$1 \times N$
First single image distance	$(3\ L_\pi)$	(L_π)	$(3\ L_\pi)/4$
First N-fold image distance	$(3\ L_\pi)/N$	$(L_\pi)/N$	$(3\ L_\pi)/4\ N$
Excitation requirements	none	$c_\nu = 0$ for $\nu = 2, 5, 8 \ldots$	$c_\nu = 0$ for $\nu = 1, 3, 5 \ldots$
Input(s) location(s)	any	$y = \pm W_e/6$	$y = 0$

Example

- MMI:
  - Si core (3.47@1550 nm)
  - SiO2 cladding (1.444@1550 nm)
  - W_d = 5 um

```
n_c = 1.444
n_r = 3.470
lambda_0 = 1550e-9
k_0 = 2*np.pi/lambda_0
W_m = 5e-6
c0  = 299792458
```

```
sigma = 0 #TE mode
We = W_m + (lambda_0/np.pi)*((n_c/n_r)**(2*sigma))*(n_r**2 - n_c**2)**(-0.5)
print(We)
```

```
5.156366792922614e-06
```

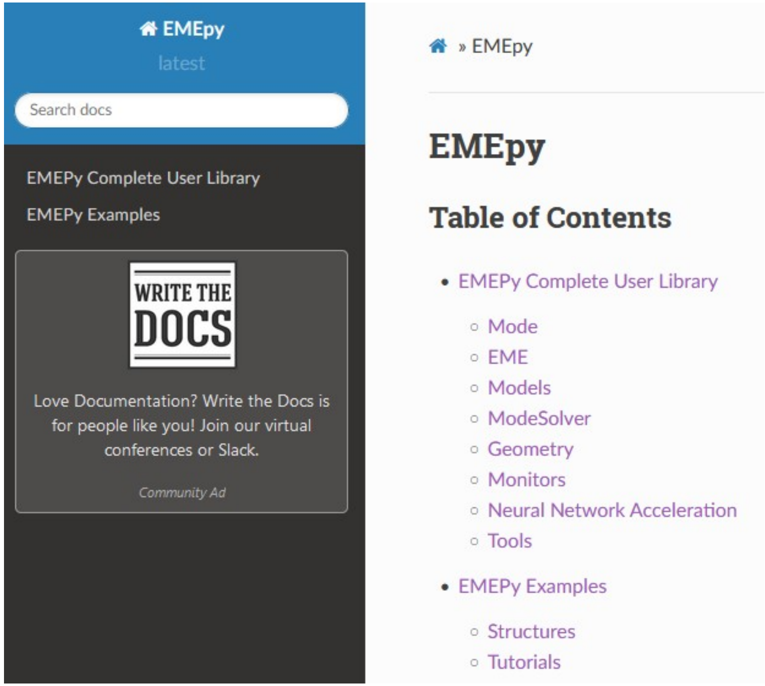
```
L_pi = 4*n_r*We**2/(3*lambda_0)
print(L_pi)
```

```
7.936410426318109e-05
```

```
np.pi/(betaTE[0]-betaTE[1])
```

```
7.918680272742915e-05
```

Using numerical methods



Example

- MMI:
  - Si core (3.47@1550 nm)
  - SiO2 cladding (1.444@1550 nm)
  - W_d = 5 um
  - Heigth = 220 nm

```
n_c = 1.444
n_r = 3.470
lambda_0 = 1550e-9
k_0 = 2*np.pi/lambda_0
W_m = 5e-6
c0  = 299792458
```

```
sigma = 0 #TE mode
We = W_m + (lambda_0/np.pi)*((n_c/n_r)**(2*sigma))*(n_r**2 - n_c**2)**(-0.5)
print(We)
```

```
5.156366792922614e-06
```

```
L_pi = 4*n_r*We**2/(3*lambda_0)
print(L_pi)
```

```
7.936410426318109e-05
```

```
np.pi/(betaTE[0]-betaTE[1])
```

```
7.918680272742915e-05
```

Using numerical methods

README.md

CAMFR

Forked from Sourceforge project for maintenance.

Originally written by Peter Bienstman at Ghent University, Belgium.

Introduction

CAMFR (CAvity Modelling FRamework) is a Python module providing a fast, flexible, full-vectorial Maxwell solver for electromagnetics simulations. Its main focus is on applications in the field of nanophotonics, like

References

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 13, NO. 4, APRIL 1995

Optical Multi-Mode Interference Devices Based on Self-Imaging: Principles and Applications

Lucas B. Soldano and Erik C. M. Pennings, *Member, IEEE*

Invited Paper

Overlapping-image multimode interference couplers with a reduced number of self-images for uniform and nonuniform power splitting

M. Bachmann, P. A. Besse, and H. Melchior

Integrated Power Splitters for Mode-Multiplexed Signals

Yuanhang Zhang[1], Mohammed Al-Mumin[2], Huiyuan Liu[1], Chi Xu[1], Lin Zhang[3], Patrick L. LiKawWa[1] and Guifang Li[1]

[1]College of Optics and Photonics, CREOL, University of Central Florida, USA

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Abstract: An on-chip non-center-feed MMI power splitter for mode-multiplexed signals is proposed and experimentally demonstrated for the first time.

OCIS codes: (130.3120) Integrated optics devices; (230.1360) Beam splitters