Scuola Universitaria Superiore Pisa

PHOTONICS INTEGRATED CIRCUITS

2019/20

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PHOTONICS INTEGRATED CIRCUITS, SENSORS & NETOWORKS
(PIXNET 2019-21)

Assignment No. 3
Lumerical MODE for waveguide mode analysis

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19 Nov 2019

Consider a SOI channel waveguide with a waveguide height of 220 nm and a SiO_2 cladding height of 1.5 μm

1. Compute and plot the effective index of the first four modes at λ=1.55 μm as a function of the waveguide width in the interval [300, 800] nm.
2. Compute and plot the effective index and group index (use the interpolated values of n_{mat}) of the fundamental TE-like mode as a function of the wavelength λ in the interval [1.5, 1.6]μm for a set of waveguide widths equal to 400, 500, 600 nm.
3. Using the provided file bend waveguide pcell.lms, compute the radiation losses and the mode-mismatch losses with the straight waveguide for the fundamental TE-like mode and TM-like mode (if guided) when the waveguide width is 300, 400, 500 nm and the curvature radius is 4, 5, 8 μm.

1 Abstract

This assignment mainly decribes one of the main method for mode characterization in a waveguide, called as the effective index method together with calculation of mode mismatch and radiative losses in a 90° bend waveguide. As per the three questions, firstly, I deduce the trend of effective index and group index with variations in waveguide width and wavelength in a certain range for the given geometry of the waveguide. Then,I discuss mode mismatch & radiative losses that are generally present in 90° bends. The whole assignment help me in figuring out the essential parameters that are needed to taken into consideration while designing various photonic devices based on waveguides for a given set of conditions.

2 Introduction

2.1 Effective Index

A mode in a waveguide is usually characterized by an invariant transversal intensity profile and an effective index n_{eff}. Each mode propagates through the waveguide with a phase velocity of c/n_{eff}, where **c** denotes the speed of light in vacuum and n_{eff} is the effective refractive index of that mode. It mainly signifies how strongly the optical power is confined to the waveguide core.
The waveguide dimensions determine which modes can exist. Most waveguides support modes of two independent polarizations, with either the dominant magnetic (quasi-TM) or electric (quasi-TE) field component along the transverse (horizontal) direction. For most applications, it is preferable that the waveguides operate in a single-mode regime for each polarization. This single-mode regime is obtained by reducing the waveguide dimensions until all but the fundamental waveguide modes become radiating.
For plane waves in homogeneous transparent media, the refractive index **n** can be used to quantify the increase in the wavenumber (phase change per unit length) caused by the medium: the wavenumber is **n** times higher than it would be in vacuum.
The effective refractive index n_{eff} has the analogous meaning for light propagation in a waveguide with restricted transverse extension: the β value (phase constant) of the waveguide (for some wavelength) is the effective index times the vacuum wavenumber given by:

$$\beta = n_{eff}\frac{2\pi}{\lambda} \tag{1}$$

The mode-dependent and frequency-dependent β values can be calculated with a mode solver software and depend on the refractive index profile of the waveguide.
Apart from this, the effective refractive index depends not only on the wavelength but also (for multimode waveguides) on the mode in which the light propagates. For this reason, it is also called modal index.Due to similar reasons the effective index is not just a material property, but depends on the whole waveguide design as well. Its value can be obtained with numerical mode calculations, for example. It can vary substantially near a mode cut-off.

The effective refractive index contains information on the phase velocity of light, but not on the group velocity; for the latter, one can similarly define an effective group index in analogy to the group index for plane waves in a homogeneous medium.

A common misconception about the effective refractive index is that it is a kind of weighted average of the refractive index of core and cladding of the waveguide, with the weight factors determined by the fractions of the optical power propagating in the core and cladding itself. This impression may result from the common observation that higher-order modes, e.g. of a fiber, have a lower effective index and also a lower mode overlap with the core. However, consider e.g. a step-index multimode waveguide with a high numerical aperture and large core diameter. Here, all modes overlap to nearly 100% with the core (i.e. the mode overlaps are very similar), whereas the effective indices differ substantially.

2.2 Group index

For calculating this, one obviously needs to know not only the refractive index at the wavelength of interest, but also its frequency dependence.The group index is mainly used, e.g., to calculate time delays for ultrashort pulses propagating in a medium, or the free spectral range of a resonator containing a dispersive medium.

In simple terms it is defined as the velocity with which the envelope of a pulse propagates in a medium, assuming a long pulse with narrow bandwidth (so that higher-order chromatic dispersion is not relevant) and the absence of nonlinear effects (i.e., low enough optical intensities). The group velocity of light in a medium is usually defined as the inverse of the derivative of the wavenumber with respect to angular frequency given by:

$$v_g = (\frac{\partial \kappa}{\partial \omega})^{-1} = \frac{c}{n(\omega) + \omega \frac{\partial n}{\partial \omega}} = \frac{c}{n_g(\omega)} \tag{2}$$

where $n(\omega)$is the refractive index and $n_g(\omega)$ is called the group index. The wavenumber κ can be considered as the change in spectral phase per unit length.
For light propagating in a waveguide such as an optical fiber, the group velocity can be calculated by replacing the wavenumber κ with β (the imaginary part of the propagation constant) (or replacing the refractive index **n** with the effective refractive index) in the equation given above. The deviation of that result from the group velocity in a homogeneous medium can be interpreted as the influence of waveguide dispersion.

Conclusively, the effective index of the waveguide is used to describe the phase velocity of the light, v_p. However, it is the group index that determines the propagation speed of a pulse, namely the group velocity, v_g:

$$v_p(\lambda) = \frac{c}{n_{eff}} \tag{3}$$

$$v_g(\lambda) = \frac{c}{n_g} \tag{4}$$

The group index n_g is an important parameter in photonic integrated circuit design since it is the group index that determines the mode spacing (free-spectral range) in resonators and interferometers. The group index can be related to the effective index:

$$n_g(\lambda) = n_{eff}(\lambda) - \lambda \frac{dn_{eff}}{d\lambda} \tag{5}$$

Therefore, it is very important to include both the material dispersion and waveguide dispersion to correctly predict the group index.The wavelength-dependent effective index can be simply approximated as:

For device (e.g. ring resonators) and system design, it is often preferable to describe the performance of the waveguides using compact models consisting of phenomenological parameters and fit functions. If there is no obvious physical dependency on the parameters, the results can be fitted using Taylor expansion approximations. For the waveguide simulated in this section , the wavelength-dependent effective index can be simply approximated as:

$$n_{eff}(\lambda) = 2.57{-}0.85(\lambda[\mu m]{-}1.55) \tag{6}$$

2.3 Modelling of waveguide based on effective index method to show wavelength and width dependence

Numerical modeling of optical 3D structures is often difficult, at least if the dimensions are large and the accuracy requirements high. A commonly used method for simplifying the modeling task is the use of the effective index method (EIM) to convert a 3D structure into a 2D structure. Therefore, here we model the waveguide using a numerical eigenmode solver. First, the waveguide geometry is drawn. Although fully vectorial 2D solutions are generally considered more accurate , this method provides important insights into how waveguides operate. Also, this method is computationally very fast and easy to implement, hence is mainly used for designing modulators.

2.3.1 Results & Discussion

To plot result of the first and second question of the assignment, waveguide's effective and group index is simulated via Script in Lumerical for a particular set of waveguide width and propagating wavelength range,the resuts of which are shown in Figure 1 to 7.

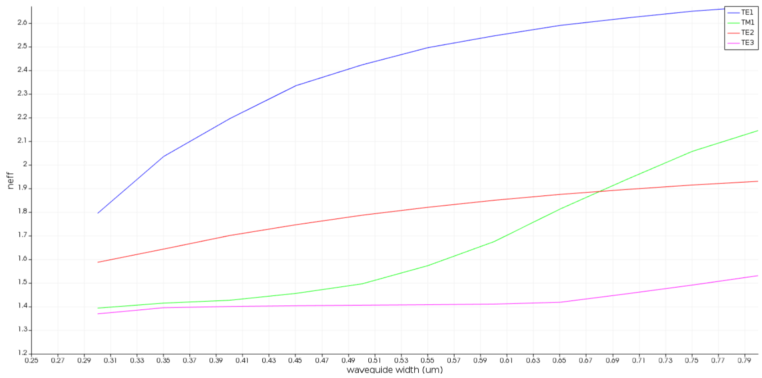

Figura 1: Plot of effective index of first four modes at $\lambda = 1.55\mu m$ as a function of waveguide width in the interval [300,800]nm

Fig. 1 shows n_{eff} as a function of the width w of the given waveguide. The n_{eff} usually depends on the waveguide cross-section, waveguide materials, and the cladding material. Higher-order modes travel with a different propagation constant compared to the lowest-order mode and are less confined in the waveguides. As a consequence of the dissimilar propagation constants, there is modal dispersion which reduces the distance-bandwidth product of the waveguide.Due to the low confinement, first, a large field decay outside the waveguide reduces the maximum density of the devices and, second, in the waveguide bends the higher-order modes become leaky resulting in propagation losses. It is therefore desirable that the difference between n_{eff} of the fundamental quasi-TE and quasi-TM modes be large enough so that the coupling between the modes is limited due to difference in mode profiles and also the phase-mismatch. The same has been depicted in the given Fig.1.

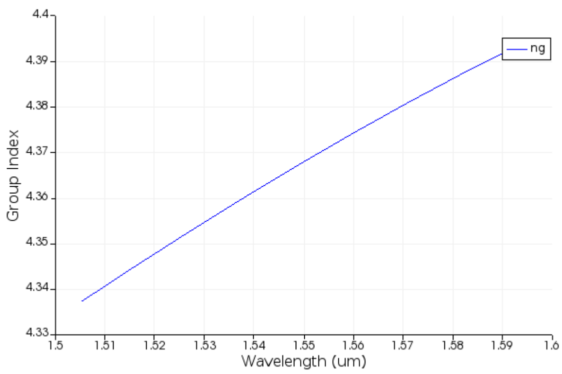

Figura 2: n_g Vs. Wavelength[1.5-1.6]μm for waveguide width=400nm

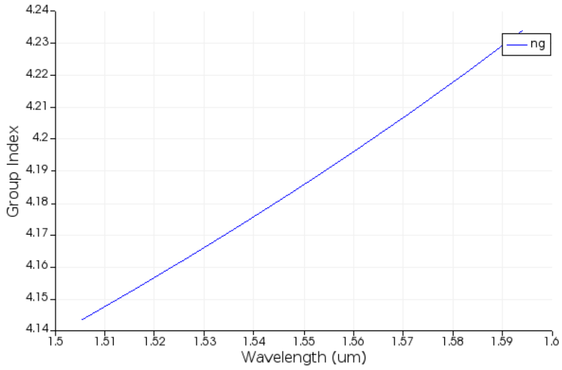

Figura 3: n_g Vs. Wavelength[1.5-1.6]μm for waveguide width=500nm

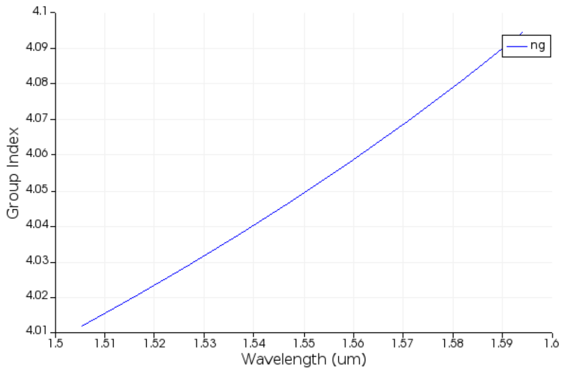

Figura 4: n_g Vs. Wavelength[1.5-1.6]μm for waveguide width=600nms

Now as per question 2, I plot graph of group index (n_g) and effective index n_{eff} as a function of wavelength for a range of wavelength ranging from $1.5\mu m - 1.6\mu m$. Fig. 2,4,6 therefore shows that the n_g increases nearly monotonically. As expected, the group index n_g, exceeds the refractive index of bulk silicon, clearly indicating that in case of photonic waveguide with strong optical confinement the propagation constant of the waveguide is dominated by the waveguides geometry and not by material properties. The observed increase of n_g, can be explained considering eq. 5, with n_{eff} as the effective index of the waveguide. Confinement decreases for longer wavelengths and as a result n_{eff} does as well. Hence, the second term including $\frac{dn_{eff}}{d\lambda}/$ becomes positive and leads to an overall increase of n_g. It is important to include both the material dispersion and waveguide dispersion to correctly predict the group index.

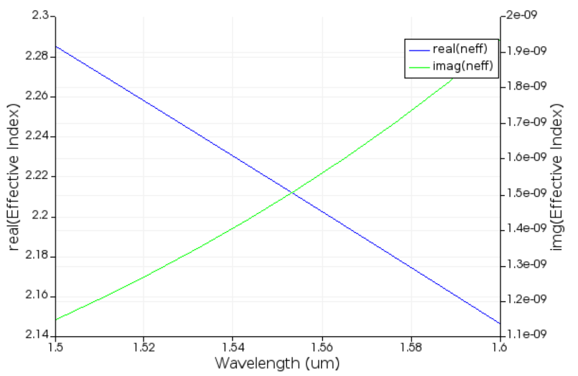

Figura 5: n_{eff} Vs. Wavelength[1.5-1.6]μm for waveguide width=400nm

Also,we know that effective Index is usually defined as the spatial average of the refractive index. In Fig. 3,5,7 the effective index decreases with wavelength. This is because, higher wavelengths have propagation near cladding, whose refractive index is lesser (relatively), thereby decreasing

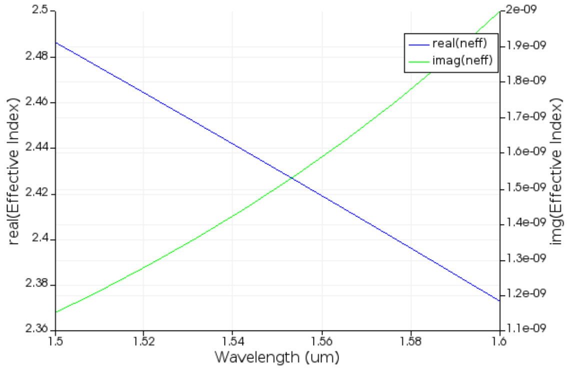

Figura 6: n_{eff} Vs. Wavelength[1.5-1.6]μm for waveguide width=500nm

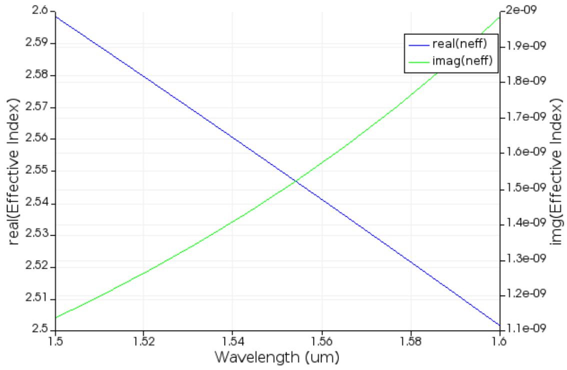

Figura 7: n_{eff} Vs. Wavelength[1.5-1.6]μm for waveguide width=600nm

the overall effective index.

2.4 Bend Loss

Losses in waveguides originate from several contributions. It may arise from absorption due to metal in proximity to sidewall scattering loss that typically comes out to be 2–3 dB/cm for 500×220nm waveguides.Surface-state absorption can also contribute to the propagation loss if the waveguides are not properly passivated. Apart from all this ,sidewall roughness also introduces reflections along the waveguide and phase perturbations that are wavelength dependent.

Waveguide losses can be reduced by using wider waveguides, though care has to be taken in single-mode applications since these waveguides are multi-mode. Hence, they require gradual tapers to convert from single-mode to the wide multi-mode waveguide.

Calculating the bend loss The bend loss has three primary contributions:

1. Mode-mismatch loss
2. Radiation loss
3. Propagation loss due to scattering

For the calculations, we consider a 90° bend, that is connected to a straight waveguide on each end.

1. Mode-mismatch loss:
this is the largest source of loss in bends. It is due to the imperfect mode overlap between the straight and the bent waveguides. This leads to scattering at the abrupt radius transition regions (start and end of fixedradius bends). There are several methods of decreasing mode-mismatch loss:

(a) to laterally offset the straight waveguide relative to the bent waveguide in order to obtain a better mode overlap

Mode-Type	Overlap Calculation	Transmission through the bend	Mode-Mismacth Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	0.97743	0.95536	0.19828
$TE_{Bend\ radius=5\mu m}$	0.988626	0.97738	0.09935
$TE_{Bend\ radius=8\mu m}$	0.996536	0.99308	0.03014
$TM_{Bend\ radius=5\mu m}$	0.803363	0.64539	1.90176

Tabela 1: Mode Mismatch Loss Values for different mode type with different bend radius having Width of Waveguide = $300nm$

(b) to vary the curvature continuously, rather than abruptly; for example a 90° bend with an effective radius of 20 μm, where curvature changes from zero to 1/15 μm^{-1} then back to zero. This has the added benefit that the bend does not excite higher order modes in the waveguide.

This is simulated using the overlap calculations. We simulate the straight-bend loss. In a 90° bend, there are two, hence we square the loss. e.g., if the overlap calculation is 0.995, the transmission through the bend (including two interfaces) is transmission through bend=$0.995^2 = 0.990$
This can also be expressed in dB as
Mode-mismatch loss, dB=$10log_{10}(0.990) = 0.043$dB

2. Radiation loss
The loss is determined in Lumerical MODE Solutions, and given in the Eigensolver Analysis window under "loss (dB/cm)". Let's call this value, as Ar. This loss includes the material absorption (which is almost 0 for silicon and silicon dioxide), as well as the radiation loss. The radiation loss originates in MODE from the PML which is perfectly absorbing.
Consider a 90° bend with a radius R. The length of the bend is

$$L = 2\pi R/4 \tag{7}$$

Hence, we find the radiation loss as

$$dB = L \times Ar \tag{8}$$

3. Propagation Loss due to Scattering
This is an experimentally measured value. It depends on the fabrication process, the mode, the wavelength, and the waveguide geometry. The propagation loss for the 90° bend is

$$Scattering\ loss, dB = L \times As \tag{9}$$

Total loss of the 90° bend
Add all these loss quantities, in dB: Total loss, dB=Mode-mismatch loss, dB+Radiation loss, dB+Scattering loss, dB . A requirement for silicon photonics is to bend waveguides, e.g. for signal routing, and ring/racetrack resonators. Thus, we must understand how much optical loss is introduced by the bend. In this section, I model the bend losses using 3D FDTD. We determine the relative contributions of radiation loss versus mode mismatch loss using an eigenmode solver tabulated in table 1 to 6.

2.5 Result & Discussion

In the tables shown below, the mode mismatch losses and radiative losses in dB has been calculated from the given file for each of the waveguide width 400,500,600nm with radius of curvature as 4,5,8μm. From the table, I observe that on increasing the radius of curvature for a given width, the mode mismatch and radiative shows a sudden downfall in their losses. This analysis thus enable me to design efficient bend in different photonic devices like MZI, by taking into account the design parameters like the width and bending radius of a particular waveguide.

Mode-Type	Overlap Calculation	Transmission through the bend	Mode-Mismacth Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	0.997803	0.99561	0.01910
$TE_{Bend\ radius=5\mu m}$	0.998614	0.99722	0.01204
$TE_{Bend\ radius=8\mu m}$	0.999466	0.99893	0.00463
$TM_{Bend\ radius=4\mu m}$	0.894063	0.79934	0.97263
$TM_{Bend\ radius=5\mu m}$	0.933522	0.87146	0.59750
$TM_{Bend\ radius=8\mu m}$	0.983891	0.96804	0.14106

Tabela 2: Mode Mismatch Loss Values for different mode type with different bend radius having Width of Waveguide = $400nm$

Mode-Type	Overlap Calculation	Transmission through the bend	Mode-Mismacth Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	0.997828	0.99566	0.01888
$TE_{Bend\ radius=5\mu m}$	0.998618	0.99723	0.01201
$TE_{Bend\ radius=8\mu m}$	0.999463	0.99892	0.00466
$TM_{Bend\ radius=4\mu m}$	0.943616	0.89041	0.50409
$TM_{Bend\ radius=5\mu m}$	0.970221	0.94132	0.26258
$TM_{Bend\ radius=8\mu m}$	0.992155	0.98437	0.06840

Tabela 3: Mode Mismatch Loss Values for different mode type with different bend radius having Width of Waveguide = $500nm$

Mode-Type	Length (L in cm)	Radiative Loss (in dB/cm)	Radiative Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	6.28×10^{-4}	119.14	0.07481
$TE_{Bend\ radius=5\mu m}$	7.85×10^{-4}	22.332	0.01753
$TE_{Bend\ radius=8\mu m}$	12.56×10^{-4}	0.26192	0.00032897152
$TM_{Bend\ radius=5\mu m}$	7.85×10^{-4}	3389.9	2.6610715

Tabela 4: Radiative Loss Values for different mode type with different bend radius having Width of Waveguide = $300nm$ considering a 90 ° bend angle

Mode-Type	Length (L in cm)	Radiative Loss (in dB/cm)	Radiative Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	6.28×10^{-4}	0.0036001	0.0000022608628
$TE_{Bend\ radius=5\mu m}$	7.85×10^{-4}	0.0002925	0.0000002296125
$TE_{Bend\ radius=8\mu m}$	12.56×10^{-4}	0.00025663	0.0000003223272
$TM_{Bend\ radius=4\mu m}$	6.28×10^{-4}	1541.4	0.9679992
$TM_{Bend\ radius=5\mu m}$	7.85×10^{-4}	718.29	0.5638576
$TM_{Bend\ radius=8\mu m}$	12.56×10^{-4}	55.064	0.0691603

Tabela 5: Radiative Loss Values for different mode type with different bend radius having Width of Waveguide = $400nm$ considering a 90 ° bend angle

Mode-Type	Length (L in cm)	Radiative Loss (in dB/cm)	Radiative Loss (in dB)
$TE_{Bend\ radius=4\mu m}$	6.28×10^{-4}	0.00047817	0.00000030029076
$TE_{Bend\ radius=5\mu m}$	7.85×10^{-4}	0.00048476	0.0000003805366
$TE_{Bend\ radius=8\mu m}$	12.56×10^{-4}	0.0004916	0.0000006174496
$TM_{Bend\ radius=4\mu m}$	6.28×10^{-4}	488.4	0.3067152
$TM_{Bend\ radius=5\mu m}$	7.85×10^{-4}	138.63	0.10882455
$TM_{Bend\ radius=8\mu m}$	12.56×10^{-4}	4.1341	0.0051924296

Tabela 6: Radiative Loss Values for different mode type with different bend radius having Width of Waveguide = $500nm$ considering a 90 ° bend angle

3 Conclusion

A modal analysis on the silicon-on-insulator waveguide was performed using Lumerical MODE. The effective index and group index were studied and their dependence on wavelength & width of the waveguide was shown graphically. Also, the losses in a waveguide was discussed and the radiative and mode mismatch losses in a bent waveguide were computed.