APSS Application Note on

Design of Ridge Waveguides

Design and simulation using APSS

APN-APSS-RidgeWG

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Abstract

This application note provides an overview of how to use the Apollo Photonics Solution Suite (APSS) to design and simulate a ridge waveguide.

This application note:

- describes the operation principle
- discusses key issues affecting ridge waveguide design, such as single-mode condition, polarization dependence, bend effects, and coupling issues
- provides tips about using the APSS Waveguide Module (APSS-WM) to improve the efficiency of the design

Keywords

Apollo Photonics Solutions Suite (APSS), waveguide module, polarization dependence, polarization coupling, bending loss, perfectly matched layer (PML)

Table of Contents

1 Introduction

The ridge waveguide, as shown in Figure 1, is a common waveguide structure and is widely used for semiconductor lasers, modulators, switches, and semiconductor optical amplifiers, as well as some passive devices.

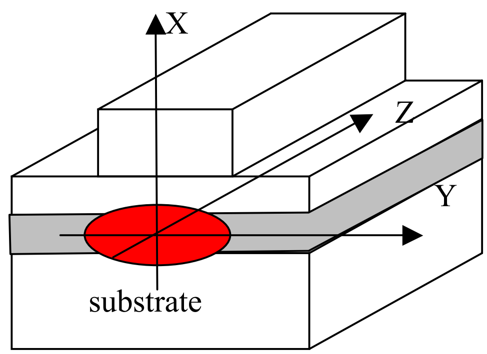


Figure 1 Schematic diagram of typical ridge waveguides

This application note discusses a number of design considerations for the ridge waveguide, including single mode condition, polarization dependence, coupling issues, and bend loss. The operation principle of the ridge waveguide is described first in order provide a context for understanding these design considerations. A quick description of each of the design considerations is provided here:

- Single mode condition – required for an effective ridge waveguide design. The single mode condition is achieved by carefully controlling the lateral confinement, and adjusting the ridge width and etching depth.
- Polarization dependence – the average ridge waveguide is polarization dependent. Polarization independence can be achieved only by deep etching and is generally impractical.
- Coupling – the effects of the geometric parameters on the coupling efficiency must be considered.
- Bend loss – due to inevitable bends in the design of the application, the effects of the bending on different aspects, including single mode condition, phase loss and polarization dependence must be considered.

2 Theory

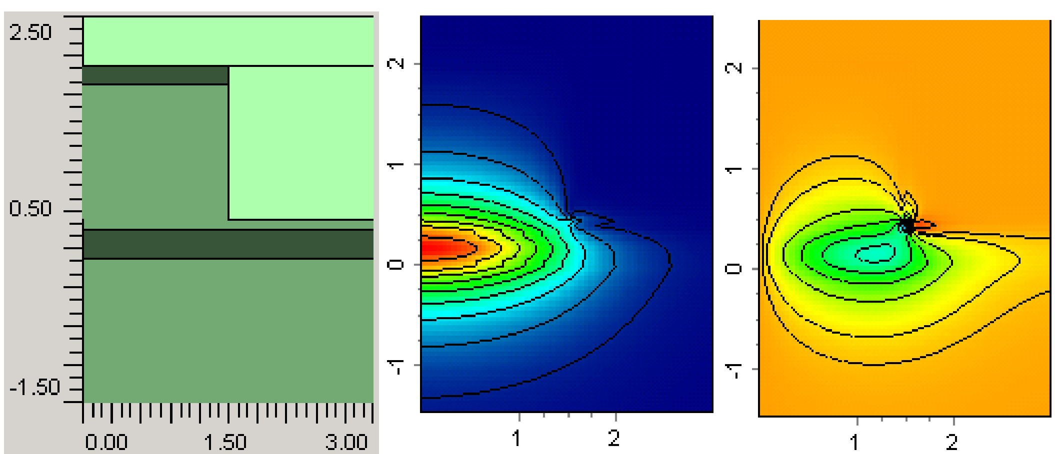
2.1 Full-vectorial versus semi-vectorial mode

From the Maxwell's equations, one can directly derive the Holmholtz equations for a straight waveguide in the Cartesian coordinator system [1].

$$\begin{bmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \beta^2 \begin{bmatrix} E_x \\ E_y \end{bmatrix} \tag{1}$$

The solutions, that is, the eigenvalue and eigenvector, of the above eigen-equation are called modes. In general, the mode of a general waveguide is both polarization dependent $(P_{xx} \neq P_{yy})$ and polarization coupled $(P_{xy} \neq 0, P_{yx} \neq 0)$. Both are the result of dielectric discontinuities.

The above equations are derived directly from Maxwell's equation without making any approximation. Hence, the solution is called full-vectorial mode. As evident from the formulation, a full-vectorial mode has two components. These components are shown in Figure 2, as calculated by the APSS-WM.



(a) Structure **(b) dominant Ex component** **(c) minor Ey component**

Figure 2 A full-vectorial mode of a ridge waveguide

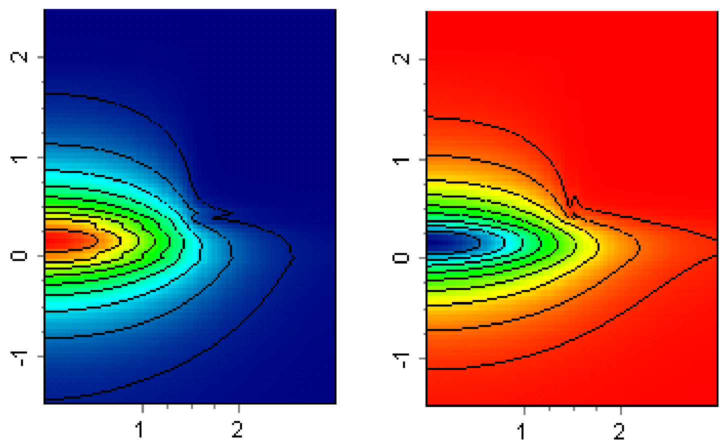
Note that one component is dominant and another component is small. The peak ratio is about 14.0/3.3 ~4 times with 0.05µm x 0.05µm meshes. Due to the singularity at the corners [2], the sharp peak of the minor component will further increase if smaller meshes are used.

When the minor component is small, it can be ignored by letting $P_{xy}=P_{yx}=0$. Then, the full-vectorial equation can be broken down into two decoupled "semi-vectorial" equations.

$$P_{xx}E_x = \beta_x^2 E_x \tag{2}$$

$$P_{yy}E_y = \beta_y^2 E_y \tag{3}$$

Solutions to the semi-vectorial equations are called semi-vectorial modes, which have only one component, as shown in Figure 3.



(a) X-polarization (E_x field) **(b) Y-polarization (E_y field)**

Figure 3 Two semi-vectorial modes of the InGaAsP/InP based ridge waveguide

In addition to the difference in modal profiles, the difference in effective indices between semi-vectorial and full-vectorial modes is also important. Figure 4 shows the calculated effective indices for both polarizations. The differences are shown in the smaller overlaid graph. The difference is about 0.0005 µm, which is too small to impact some applications and too big to be feasible for use in other applications.

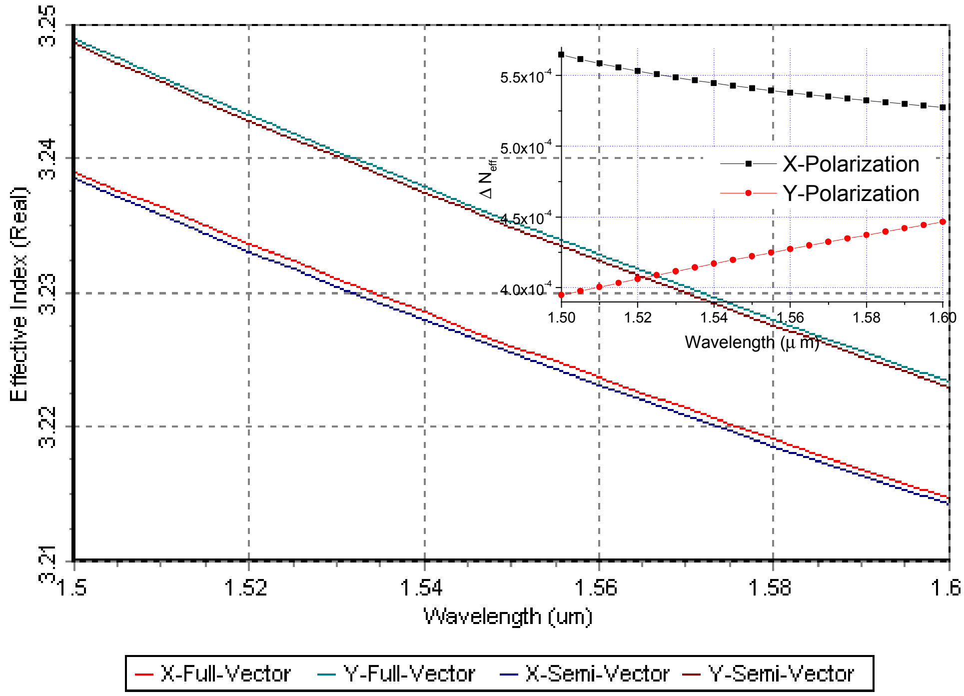


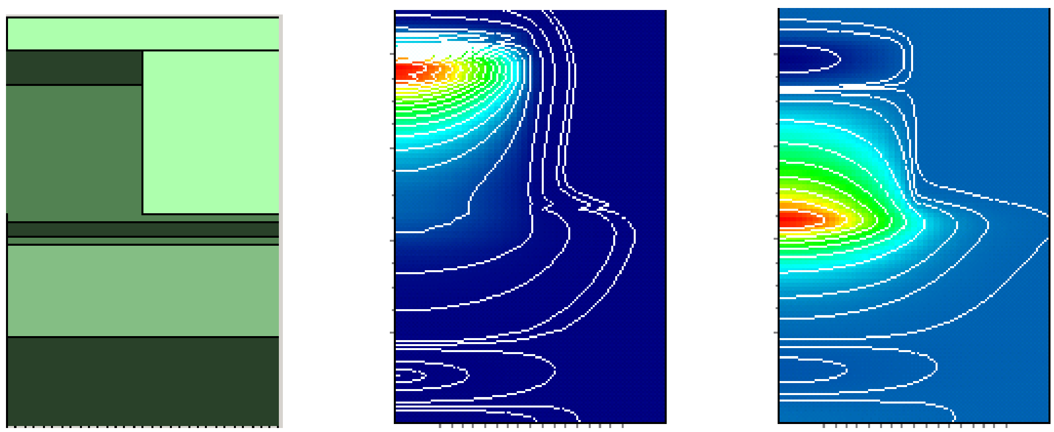
Figure 4 Effective indices of the ridge waveguide

2.2 Guided mode versus leaky mode

Mathematically, the number of eigen-states is the same as the number of meshes used in the calculation. Some have real propagation constants (or "effective indices"), but most have complex propagation constants. Those with real effective indices are called "guided mode" because they have no propagation loss. Those with complex effective indices are said to be in "leaky mode" because they do have propagation loss.

This application note primarily focuses on guided modes because the leaky modes are lost during propagation anyway. However, there are some exceptions where the leaky mode is required to achieve specific design objectives. For example, all modes of an AlGaAs/GaAs laser waveguide structure, as shown in Figure 5(a), are leaky modes, because of the high refractive index of the GaAs substrate. Because the effective index of the mode is lower than the refractive index of the substrate, the tunneling effect will cause the mode to leak into the substrate as shown in Figure 5(b-c). This application note only deals with the mode confined in the active layer as shown in Figure 5(c) because it will survive due to the gain in the active layer. The other modes are not as important, including the mode confined on the top of the ridge as shown in Figure 5(b). This mode exists but cannot survive for two reasons:

- it is far away from the active layer, so there will be little gain
- it is close to contact with metal and therefore will suffer large absorption



(a) Structure (b) Undesired mode (c) Desired mode

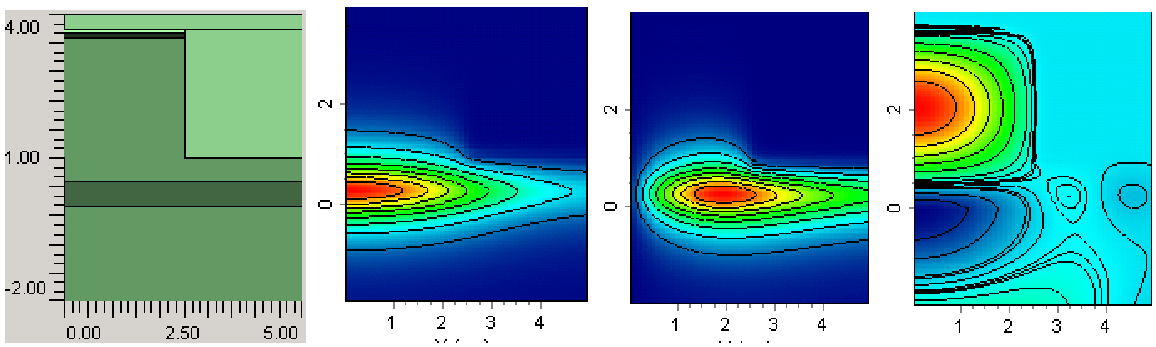
Figure 5 Structure and modal profiles of a AlGaAs/GaAs waveguide

2.3 Fundamental mode and higher order mode

The calculated eigen-modes are ordered according their eigen-values, that is, effective indices, from large to small. The mode with the highest effective index is called the "fundamental mode" and all the others are called "high order modes".

Figure 6(a) shows a typical structure based on InGaAsP/InP material system. Its fundamental mode fundamental mode, and the 1st high order anti-symmetric mode in the lateral direction are shown Figure 6 (b) and (c), respectively. In addition, there is an unconventional mode confined inside the ridge, as shown in Figure 6(d).

The existence of this unconventional mode may be a surprise to some designers. It can affect device performance significantly, especially for passive devices. Because its modal profile is round, it can therefore match fiber modes even better than the fundamental mode. As a result, it can be fairly easy for a designer to accidentally align to the wrong mode and unintentionally make the device dysfunctional. Although this unconventional mode is leaky, it is still potentially harmful because semiconductor devices are typically short. Unfortunately, it is very difficult to eliminate this mode.



(a) Structure **(b) Fundamental mode** **(c) Anti-symmetric mode** **(d) Ridge mode**

Figure 6 InGaAsP/InP ridge waveguide structure and its modes

The AlGaAs/GaAs ridge waveguide shown in Figure 5 is another example. The mode confined in the active layer, shown in Figure 5(c), is the fundamental mode, while the others are the high order modes, including the mode confined on the top of the ridge as shown in Figure 5(b). Even though the effective index of this mode from the top of the ridge is higher than the fundamental mode, it is still considered a high order mode because it cannot survive.

2.4 Single mode and multimode

It is not easy to set a universal criterion of so-called single mode, although it might be provisionally defined as satisfying this statement: Only the fundamental mode is guided and all other modes are cutoff. The problem with this statement is that there is no clear definition of "cutoff".

Even with a clear mathematical definition of "cutoff", there is, physically, no clear line between guided and unguided modes. Unguided modes, especially those slightly below cutoff, may have very small propagation loss, and for this reason, the mode may be able to survive very long distance. This will typically affect the performance of the device unless the device is long enough.

At a practical level then, the three following criteria can be used to judge if a mode is to be considered guided:

- The effective index is higher than index of claddings.
- The modal profile is confined (within the core).
- The mode is not leaky.

Please note that not every rule is applicable to every waveguide structure. These different criteria are discussed in the subsections that follow.

2.4.1 Effective index-based criterion

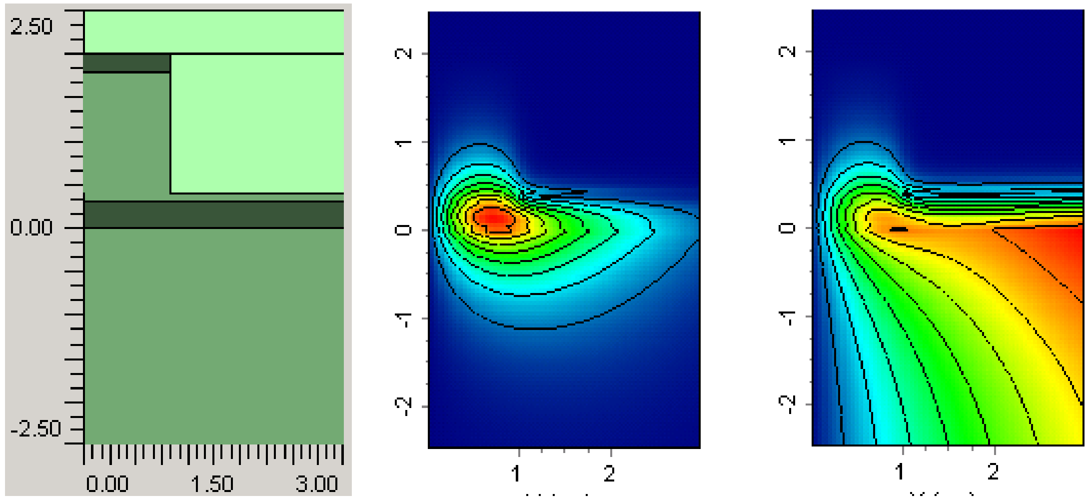
That the effective index must be higher than the cladding for a mode to be considered "guided" is applicable to waveguides that are surrounded by claddings with a lower effective index. This includes optical fibers or buried channel waveguides.

However, this rule is not applicable to ridge waveguides because in ridge waveguides, the core is sandwiched by the claddings, and the effective index is always bigger than the refractive index of the claddings, regardless of whether the mode is guided or unguided.

2.4.2 Modal confinement-based criterion

Guided modes are usually confined to the core region, while unguided modes are not.

However, in some cases, the mode is not confined even when the effective index is well above the index of the cladding. The InGaAsP/InP waveguide shown in Figure 7(a) is an example of this. The first anti-symmetric mode, or the first high order mode is confined well inside the rib at the wavelength λ=1.55µm, as shown in Figure 7(b). It becomes unconfined at the wavelength λ=1.75µm, and hence the waveguide is determined to be single-mode.



(a) Structure at W=2μm **(b) Confined at λ=1.55μm** **(c) Unconfined at λ=1.75μm**

Figure 7 InGaAsP/InP ridge waveguide structure and its 1st anti-symmetric modes

In general, it is easiest to judge whether a mode is guided or unguided by analyzing the modal profile. However, although this method is applicable to all kinds of waveguides, it is subjective, requires experience, and is not mathematically precise.

2.4.3 Leakage-based criterion

Another way to judge whether a mode is guided or not is to examine the propagation loss of the mode, or the imaginary part of the effective index. By using the Perfectly Matched Layer (PML) boundary condition that is available in the APSS-WM, the designer can make the simulation absorb the leaky wave and then calculate the amount of leakage[3]. Figure 8 shows the calculated leaky loss of the first anti-symmetric mode of the InGaAsP/InP ridge waveguide, shown in Figure 7 with W=3μm.

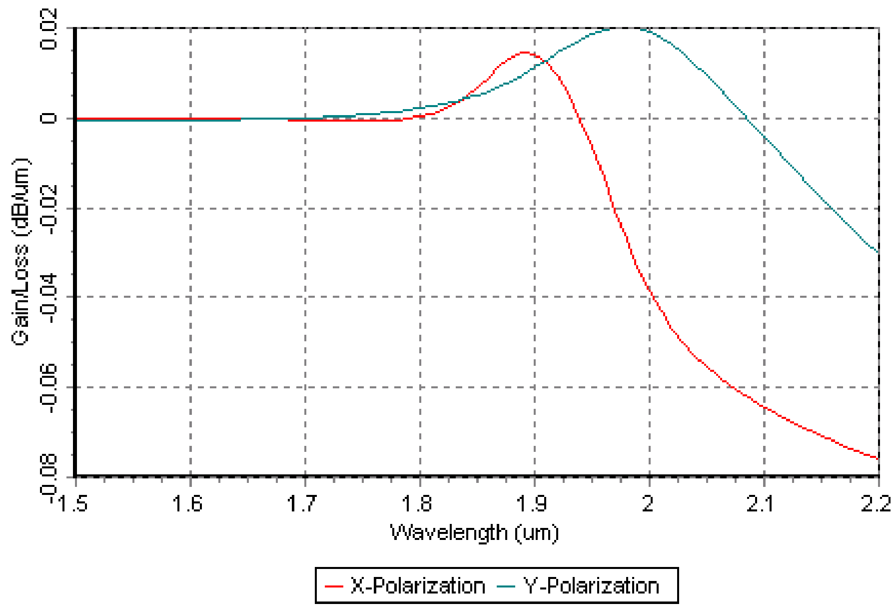


Figure 8 Leakage of the first anti-symmetric mode of the InGaAsP/InP ridge waveguide

As shown above, the mode is guided and has no loss on the short wavelength side, but experiences loss and is unguided on the longer wavelength side. However, minor gain is observed because the PML boundary condition was used unnecessarily – where the mode is not leaky. The PML boundary condition makes the mesh size complex and turns an exponential decay wave:

$$E(x) = e^{-\alpha x} = e^{-\alpha(x_r - jx_i)} = e^{-\alpha x_r} e^{j\alpha x_i} \tag{4}$$

into a traveling wave, which travels inward to the computational window and unfortunately introduces gain.

For these reasons, the PML boundary condition must be used judiciously to avoid undesired results. For example, because the wave mostly leaks in the lateral direction and into the substrate, the PML boundary condition should be used exclusively for the right (Y_{max}) and bottom (X_{min}) boundaries.

Although there is no clear "cutoff" between guided and unguided modes in practice, "cutoff" can be defined, for convenience, as the zero loss point. Then, according to specific applications, the high order mode can be designed with whatever level of leakage is required to ensure single mode operation[4].

This criterion is not applicable to waveguides with either material absorption or intrinsic leakage because these contribute to the imaginary part of the effective index. For example, this criterion is not applicable to GaAs based waveguides.

3 Design and Simulation

3.1 Single mode condition

In order to make the waveguide single mode, all the high order modes, specifically the first anti-symmetric mode and the ridge mode as shown in Figure 6 (c) and (d), must be below cutoff.

To understand the confinement mechanism of the modes under the ridge, imagine that the ridge is a piece of magnet and the modes in the core are pieces of iron that are attracted by the magnet. Reducing the ridge width and height is like reducing the size of the magnet. Reducing the etch depth is like increasing the distance between the magnet and the iron. Increasing the thickness of the core is like increasing the size and weight of the iron. All of these actions will weaken the attraction between the magnet and the iron.

To cut off the anti-symmetric mode, the lateral confinement can be reduced by doing one of the following:

- reducing the ridge width
- reducing the etching depth, (that is, reducing the distance the core from the ridge)
- reducing the ridge height
- increasing the thickness of the core

Using the scanning capability of the APSS, a geometric parameter can be looped. The effect(s) of several different parameters will be investigated in the following sections.

3.1.1 Effect of ridge width

According to waveguide processing technology, the waveguide width is the easiest parameter to vary after the wafer is ordered. Different width can be used anywhere on a wafer, so it makes sense to investigate width issues first.

Figure 9 shows the calculated leak loss of the anti-symmetric mode of the ridge waveguide for both polarizations as a function of ridge width. Other parameters are: D_1=0.5µm, D_2=3µm, D_3=0.1µm, D_4=0 (excluding the metal layer), and H=2.6µm. For the sake of comparison, both full-vectorial and semi-vectorial results are shown in the same chart. It is observed that:

- There are few differences between full-vectorial and semi-vectorial results. Semi-vectorial will be used for the rest of the investigation because it used four times less memory and at least four times less computation time;
- The Y-polarized anti-symmetric mode reached cutoff earlier than the X-polarization, even though its effective index is higher than its counterpart.
- The waveguide becomes “single” mode when W<4.7µm.

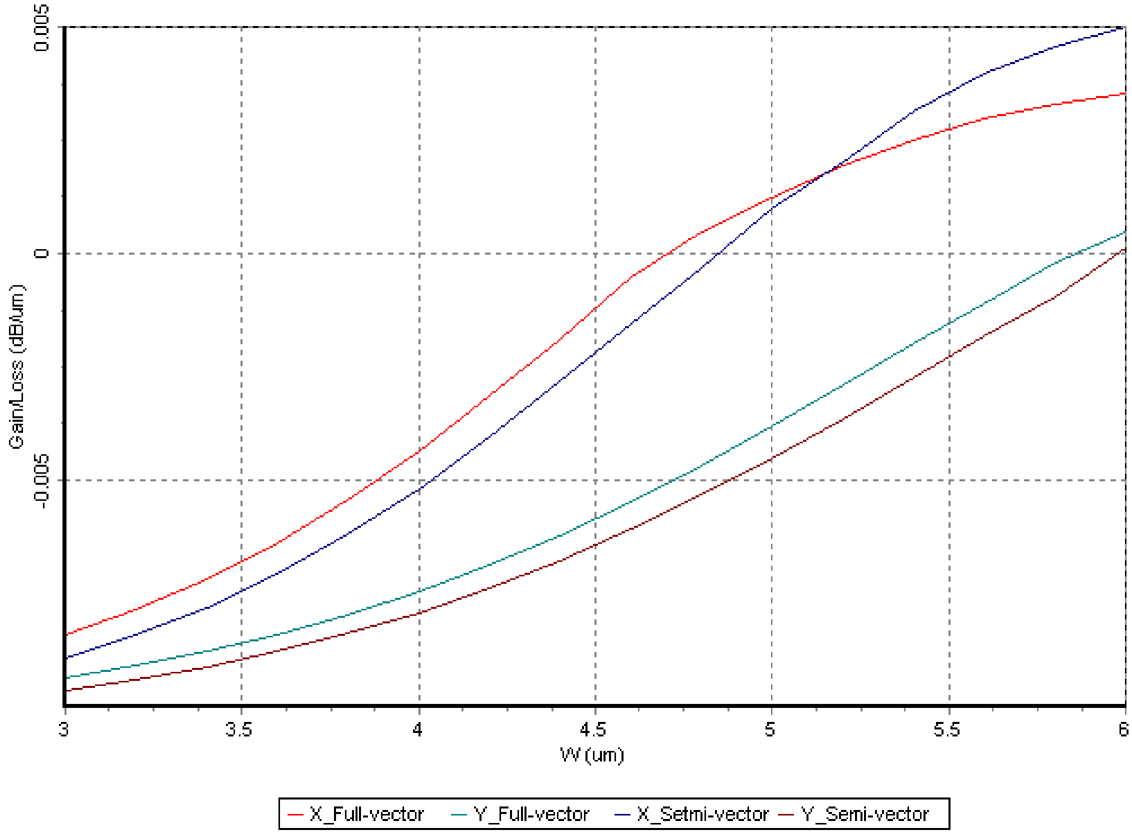


Figure 9 Leakage of the anti-symmetric mode of the ridge waveguide at different ridge width

Mesh settings in the APSS must be set correctly to achieve accurate results. Specifically, the following must be noted:

- Uniform meshes are used during scanning, regardless of what mesh distribution is used in the simulation.
- The incremental of the variable should be an integer number of mesh size to achieve smooth and consistent results.
- For a half structure, the incremental in the lateral direction, such as ridge width, should be double the integer number of the mesh size, because only half is shown in the window.

3.1.2 Effect of ridge height

Reducing the ridge height reduces the overall size of the ridge and weakens the lateral confinement. Figure 10 shows the calculated leakage as a function of ridge height at a fixed ridge width W=6.0μm. During the scan, we let the thickness of the second layer be D_2=0.5+H-D_3-D_4 to ensure that the thickness of the upper side cladding was a constant 0.5μm. Also, to ensure the mesh size remained unchanged during the scanning, the vertical window was made a constant by letting Ds=6-D1-D2-D3-D4-Dc. It is observed that:

- The ridge height has little effect on the anti-symmetric mode, and the effect is saturated very quickly.
- The single mode condition could be easily satisfied when H<0.52μm.

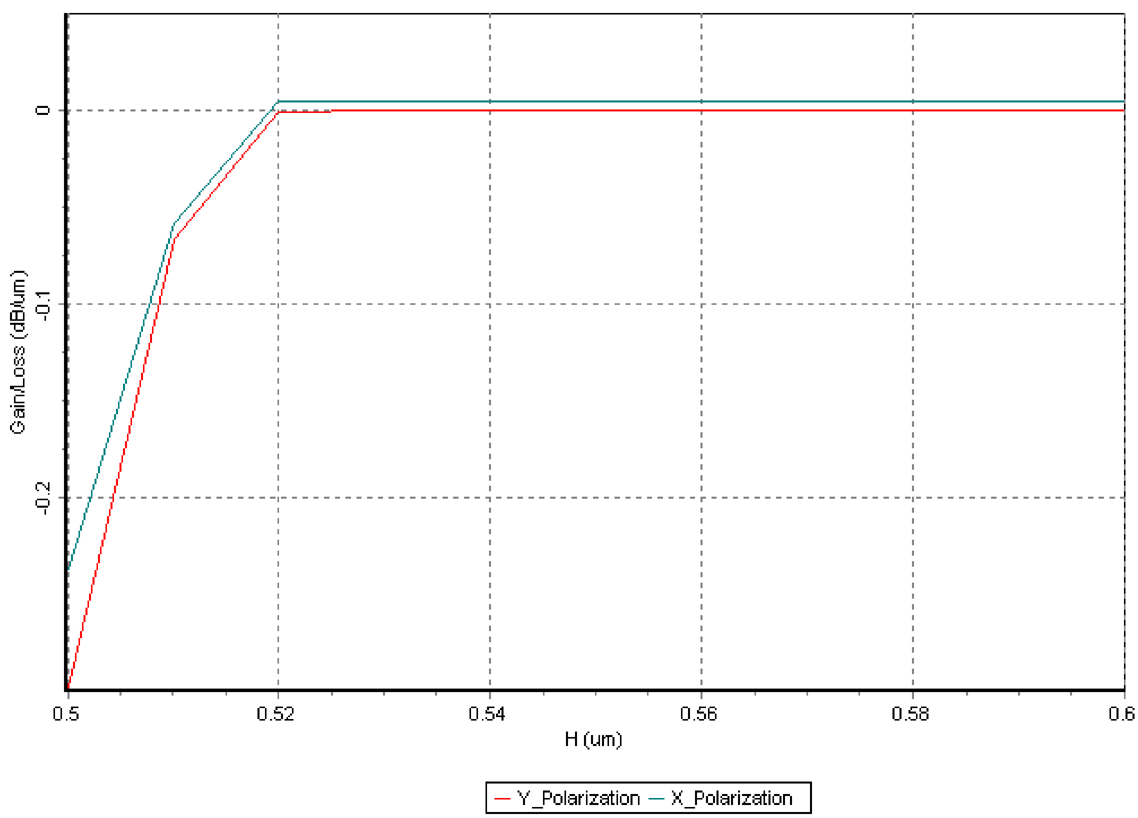


Figure 10 Leakage of the anti-symmetric mode of the ridge waveguide at different ridge height

3.1.3 Effect of etching depth

Unlike the width, etching depth should be uniform over the entire wafer, and it is in fact difficult to vary etching depth on the same wafer. Reducing the etching depth (increase the thickness of the upper side cladding, equivalently) is another option to cut off the anti-symmetric mode is to decrease the etching depth. Figure 11 shows the calculated leakage as a function of ridge width at a fixed ridge width W=5µm. Similar behaviors as have been already observed occur, and the waveguide becomes "single" mode when H<2.56µm.

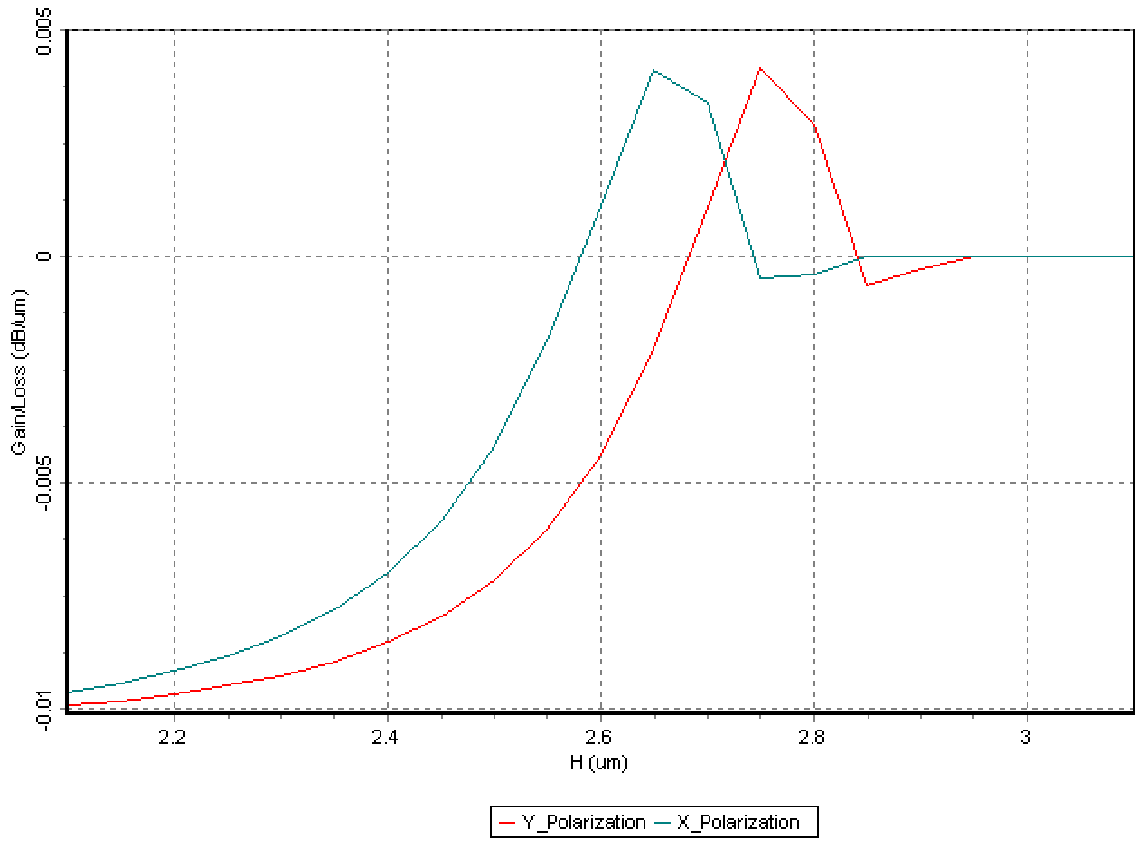


Figure 11 Leakage of the anti-symmetric mode of the ridge waveguide at different etching depth

3.1.4 Effect of core thickness

Although increasing core thickness is another option theoretically, on a practical level changing the core thickness is not desirable. A thick core has a lot of side effects, such as higher thresholds for lasers, and introduces poorer saturation characteristics for a semiconductor optical amplifier (SOA).

3.1.5 Ridge mode

Another challenge is to minimize the effect of the intrinsic ridge mode as shown in Figure 6(d). This mode is like water in and the ridge is like a sponge that soaks up the water. The mode hides inside the ridge, with some leakage, and it is difficult to get the mode completely out of the ridge. The ridge can be "squeezed", by reducing the ridge height. This leaves less room for the ridge mode and forces it to leak more. However, if the ridge is made too small, it will negatively affect the fundamental mode in two ways:

- It will suffer absorption loss from contact with metal at the top.
- The modal profile of the fundamental mode will become more flat, and coupling with optical fibers will be impaired.

Figure 12 shows the calculated leakage of the ridge mode as a function of ridge height at a fixed ridge width W=5µm. As predicted, the smaller the ridge height, the more leakage.

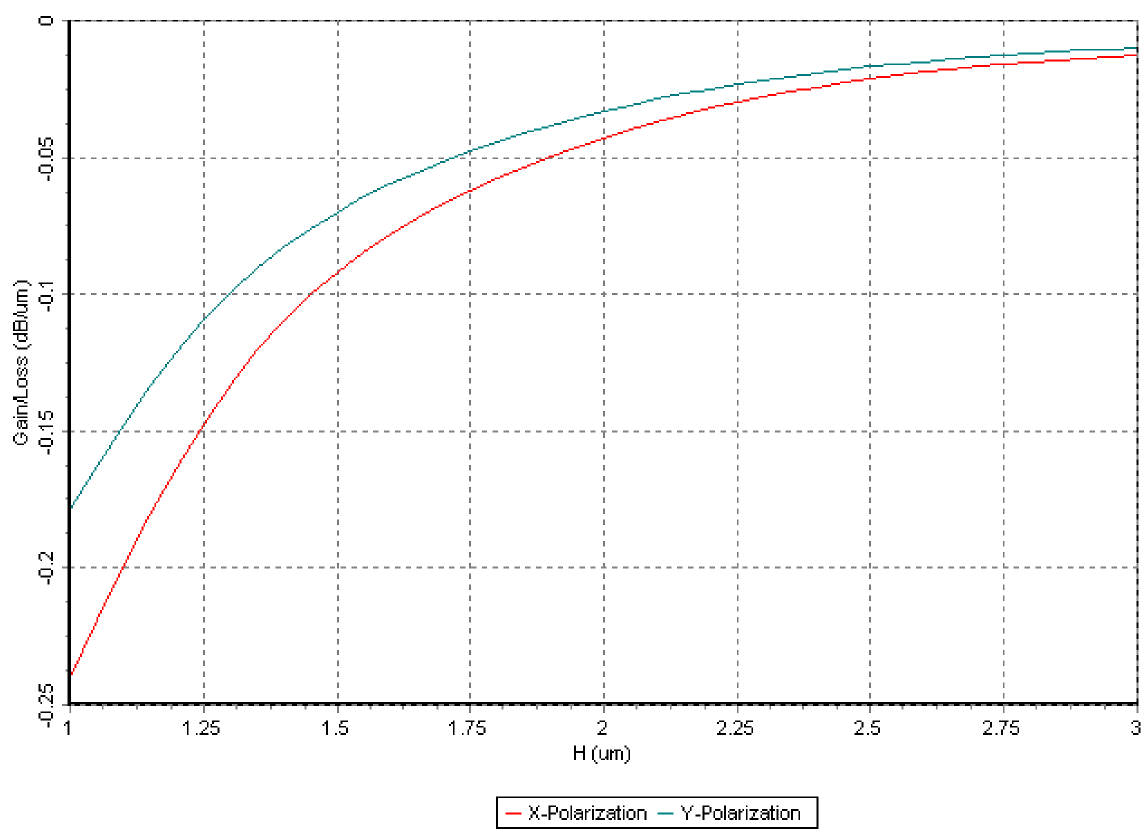


Figure 12 Leakage of the ridge mode of the ridge waveguide at different ridge height

3.1.6 Universal single mode curve

As discussed in previous sections, there are two main geometric variables, the width and etching depth, to adjust for a given wafer with fixed layer thickness and material composition. With these parameters, a universal single mode curve can be obtained by calculating the single mode width for each etching depth. Figure 13 shows the curve calculated for a InGaAsP/InP waveguide. All other parameters are same as those used in Ref[5], specifically: core (λ_g=1.1μm) thickness D_1=0.5μm, cladding (InP) thickness D_2=3.0μm and the ohmic contact thickness D_3=0.1μm. The metal layer and the etching stop layers are excluded in the calculation since they have little effect on the optical modes.

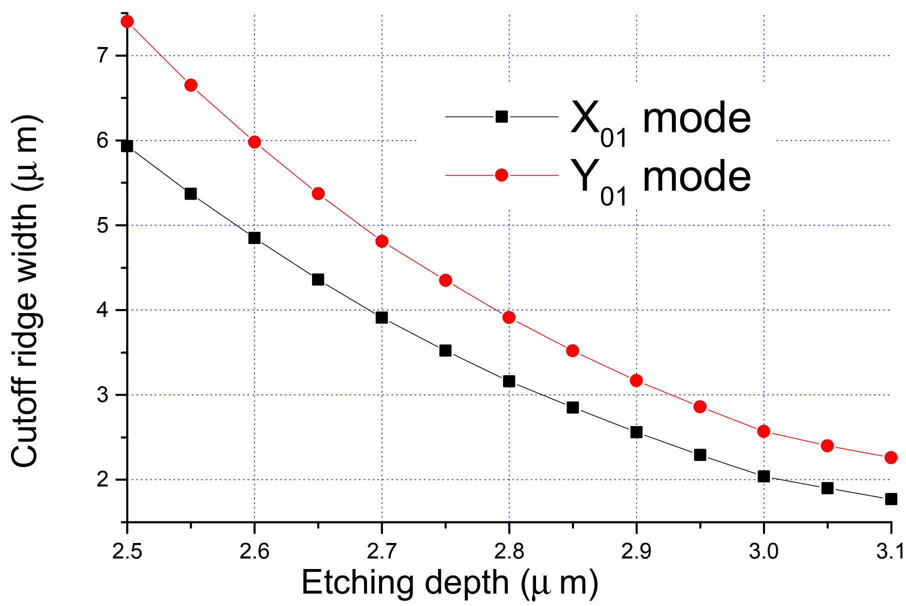


Figure 13 Universal single mode curve for a InGaAsP/InP waveguide

The results are obtained manually point by point and plotted by third party software. It is found that X-polarized anti-symmetric mode is the last high-order mode to reach cutoff, though its effective index is lower than that of the Y-polarized counterpart. Therefore, the region under X_{01} curve is the single mode region.

To obtain a similar curve for an InGaAsP/GaAs waveguide, the substrate GaAs layer can be ignored because the lower cladding is usually thick enough, and the tunneling effect is very small. Then the single mode condition can be calculated by applying the leakage based criterion.

3.2 Polarization dependence

Due to the nature of the guidance, the modal profile is very flat and the ridge waveguide is highly polarization dependent. The optimization of geometric parameters would not help significantly. Figure 14 shows the effective indices of the InGaAsP/InP waveguide for both polarizations as a function of the ridge width. It is observed that varying ridge width has little help on reducing the polarization dependence.

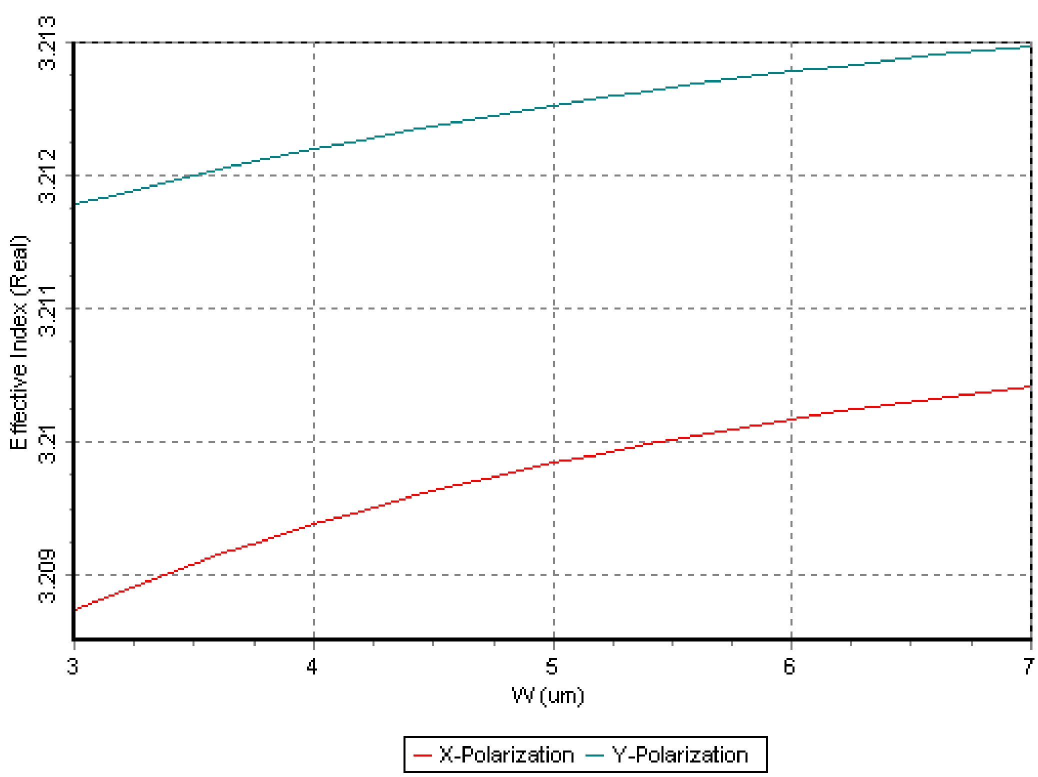


Figure 14 Modal indices of a InGaAsP/InP waveguide as a function of ridge width

However, polarization independence still can be achieved by deep etching through the core. The core is then inside the ridge and acts as a channel waveguide, as shown in the small overlaid chart in Figure 15. From the modal indices of both polarizations, shown in Figure 15, polarization independence can be achieved at ridge width W=2.2µm. At this width, the modal profile is almost round (as shown in the small overlaid chart).

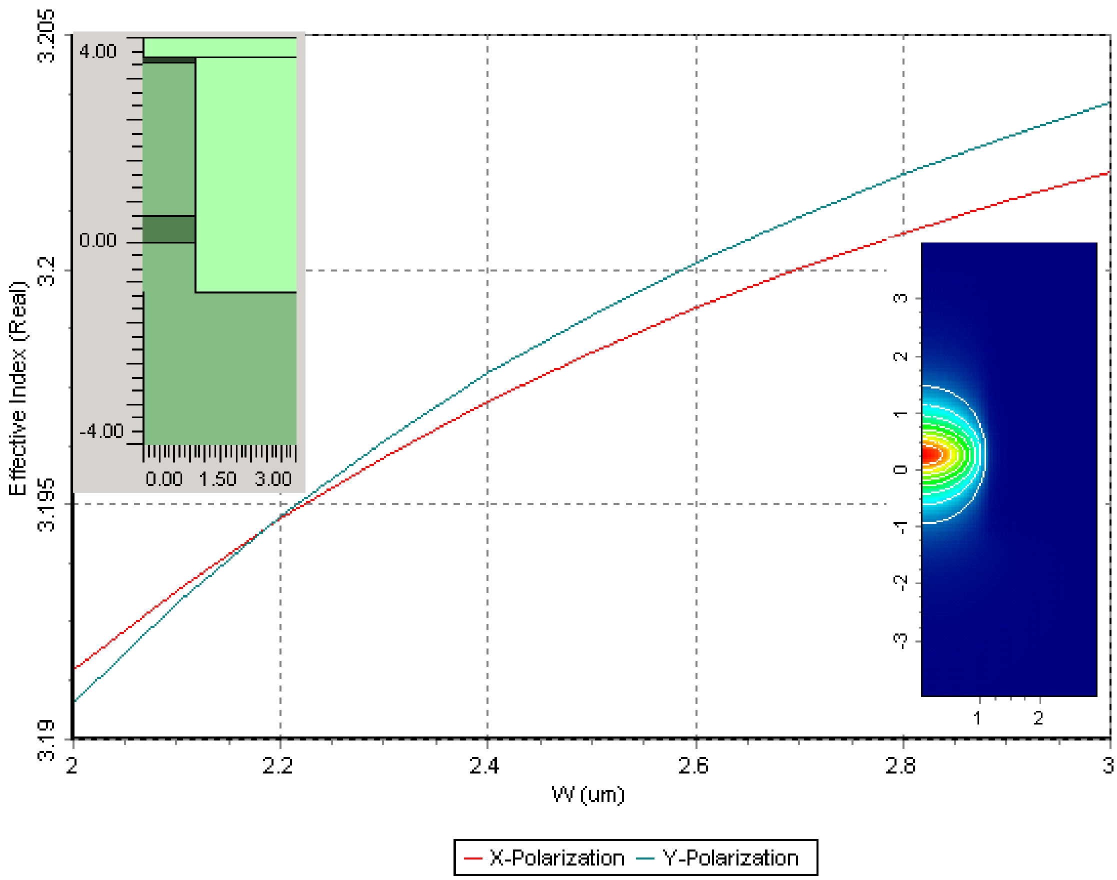


Figure 15 Structure, modal index, modal profile of a deep etched InGaAsP/InP waveguide

3.3 Coupling with optical fibers

With the single mode condition, coupling efficiency is the next concern since the waveguide will eventually be connected to optical fiber. Overlap integral is a useful feature in the APSS-WM that can be used to calculate the coupling efficiency from one waveguide to another. Figure 16 shows the scanning result of the coupling efficiency with standard Corning fiber SMF-28. The waveguide parameters are: W=5µm, D_1=0.5µm, D_2=3µm, D_3=0.1µm, D_4=0 (excluding the metal layer), and H=2.6µm. The optimal position is (-14.7,0) and the maximum butt-to-butt coupling is 32% for this structure. Please note the position is the coordinator in the lower-left corner of the second project, according to the coordinate system of the first project.

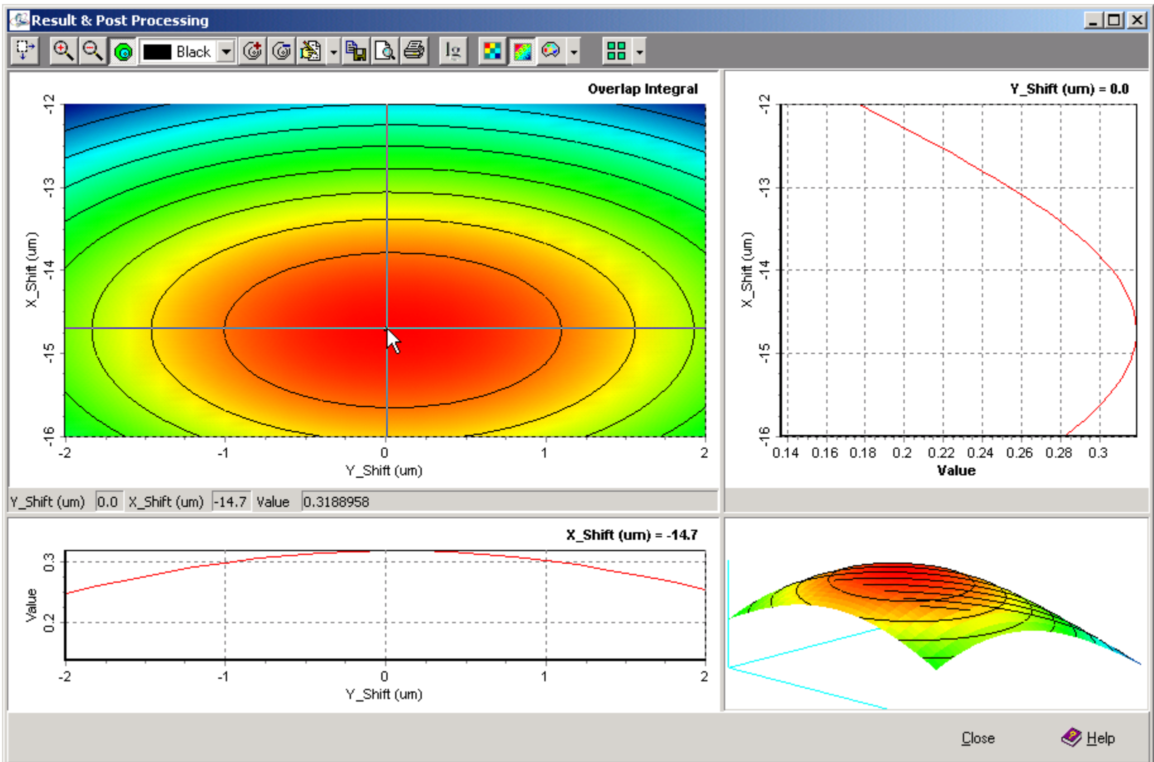


Figure 16 Coupling efficiency to optical fiber as a function of alignment position

By looping a geometric parameter and repeating the above procedure, we could obtain an optimal design curve to achieve maximum coupling to the fiber. Figure 17 shows the maximum coupling as a function of ridge width, while all other parameters are the same as above.

As expected, the coupling efficiency is improved as the ridge width increases, due to stronger lateral confinement. As a result the mode becomes round. However, the width cannot be too big if the waveguide is to remain single mode. The single mode width for this case is W<4.85µm, as was calculated earlier.

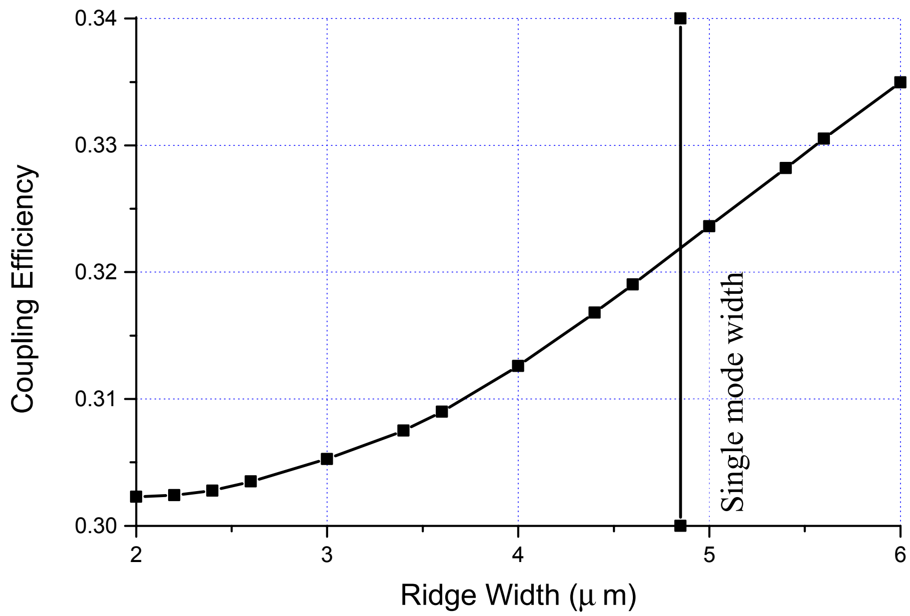


Figure 17 Maximum coupling efficiency with optical fiber as a function of ridge width

Other parameters, such as core thickness (D_1) and etching depth (H), can also be adjusted to optimize coupling efficiency, although it is important to remember that coupling efficiency is only one aspect of a waveguide design. A designer must also be aware of other effects, such as polarization dependence, bending loss, and other properties related to active devices. For example, confinement factors for optical switches and modulators, and thresholds for lasers might also be considered, although these are not addressed by APSS in its current version.

3.4 Bending effects

Bending is inevitable in most applications and it affect the modal confinement and can change the modal effective index and modal profile. They affect the single mode condition and polarization independence, and introduce phase error and bending loss. Please note that a whole structure (and not a half-structure, as is possible for some other parameters) must be used in the APSS-WM to investigate bend modes.

3.4.1 Effect on single mode condition

Bending introduces extra loss, and makes the high order mode more leaky and further strengthens the single mode condition. Therefore, bent waveguides are sometimes introduced on purpose to eliminate the high order modes from some applications.

3.4.2 Effect on phase

Due to the bend, the modal profile shifts to the outer side as shown in Figure 18. As a result, the effective optical path becomes longer and the effective index becomes higher as shown in Figure 19. Therefore, phase delay increase has to be taken into consideration for phase sensitive devices, such as AWG, and asymmetric Mach-Zenhder interferometer.

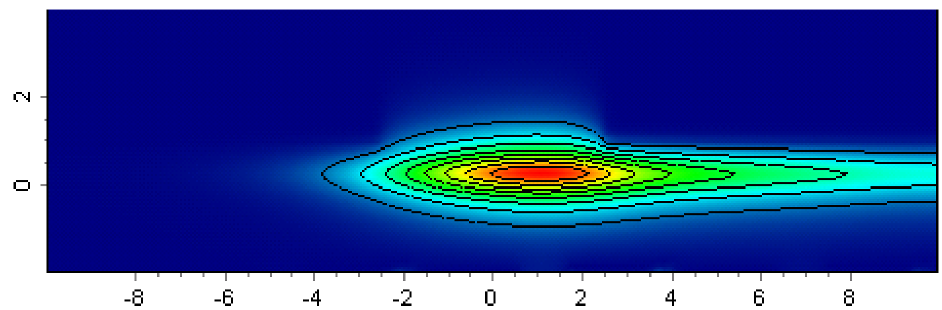


Figure 18 Modal profile of waveguide with bent radius R=5mm

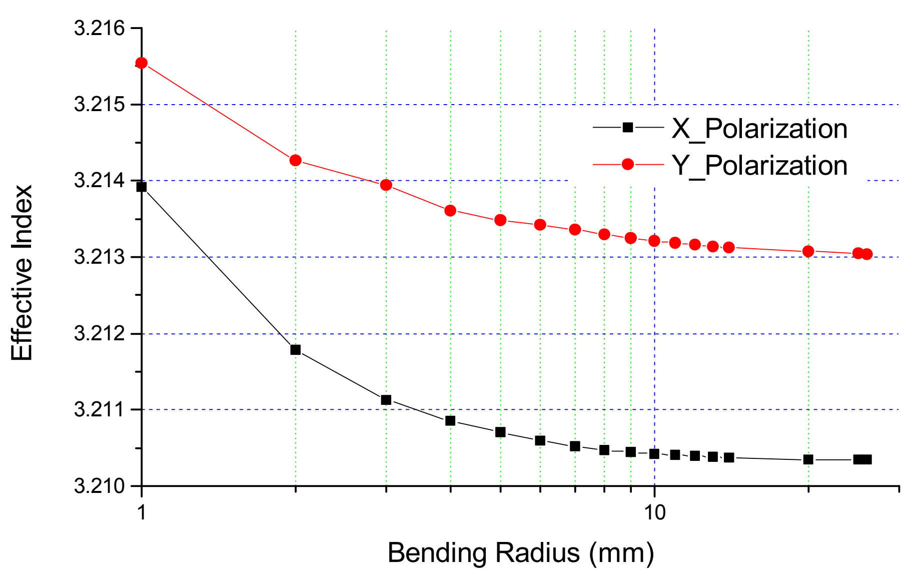


Figure 19 Effective index of the waveguide as a function of bending radius

3.4.3 Bend loss

If the bending radius is too small, the lateral confinement becomes too weak [3], the and the APSS-WM can be used to calculate the bending loss accurately. Figure 20 shows the bending loss of the ridge waveguide as a function of bending radius. This can be used as a reference for designing a bending waveguide. All the parameters are the same as before, specifically: W=5µm, D_1=0.5µm, D_2=3µm, D_3=0.1µm, D_4=0 (excluding the metal layer), and H=2.6µm. Please note, the current version of APSS-WM cannot loop any solver related parameter, such as the bent radius, and we have to obtain the data point by point.

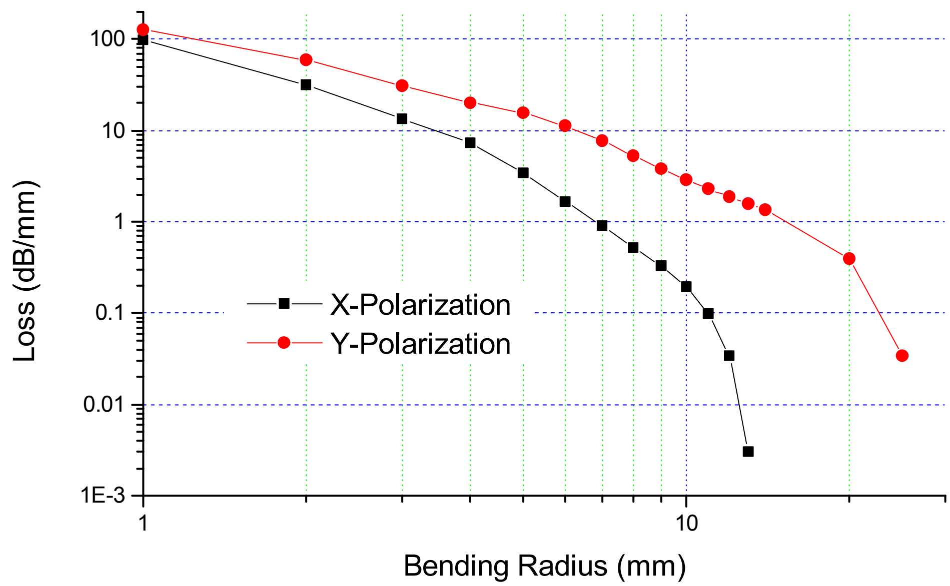


Figure 20 Bending loss of the waveguide as a function of bending radius

3.4.4 Effect on polarization dependence

Bend also breaks up the balance between two orthogonal polarizations and destroys the polarization independence achieved earlier as shown in Figure 15. However, under certain conditions, a suitable width can be determined that allows even a bending waveguide to be polarization independent. Figure 21 shows the polarization independent width at different bending radii for a deep-etched ridge waveguide.

When the bending radius is too small, polarization independence cannot be achieved by increasing width because the mode, as shown in the inserted chart, becomes a whispering gallery mode[6], which is confined by one side only.

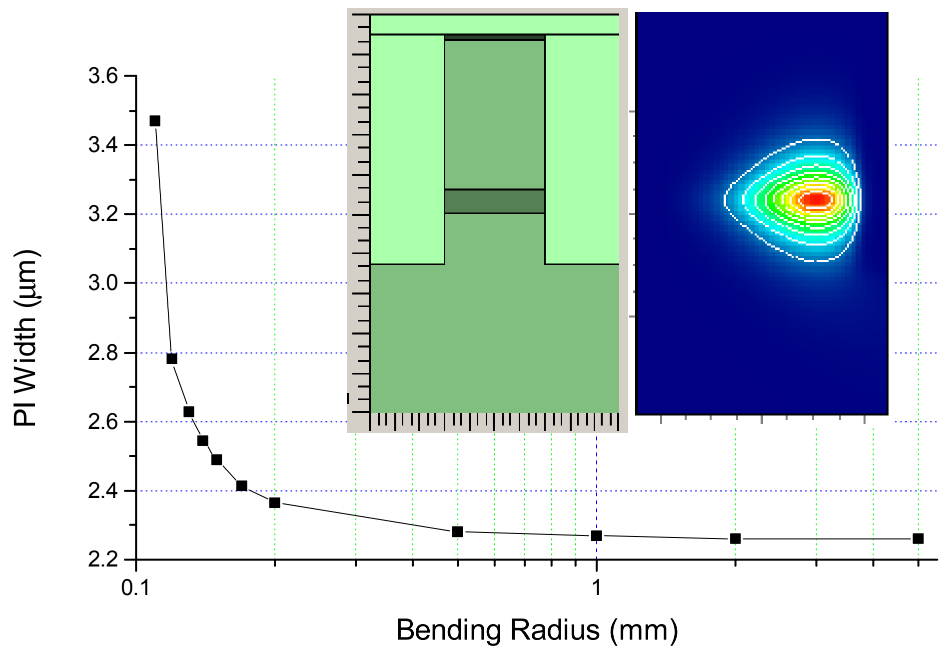


Figure 21 Polarization independent width at different bending radii

4 Discussion

There are several important aspects that must be considered when designing a ridge waveguide, and it is challenging to satisfy every requirement simultaneously. Therefore, it is recommended that designers prioritize the design requirements and compromise as required, depending on the specific application and design goals.

5 Summary and conclusion

As demonstrated with a practical example, the APSS-WM is a powerful and efficient tool for designing a complex waveguide. In particular, the parameter scanning feature is especially useful for adjusting and optimizing a design for a specific purpose.

For the first time, practical criteria for a definition of single mode have been established, although it is acknowledged that even with a clean mathematical definition of single mode, there is no clear line defining single mode in reality.

In addition to the single mode condition, other variables, such as the polarization dependence, coupling with optical fiber, and bending effects have been investigated and discussed..

6 Reference

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