


Handbook
for
Generic Photonic IC Design

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Chapter 9

Passive waveguides (draft)

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Passive waveguides are the Basic Building Blocks that guide the light in an optical circuit. They are used for interconnecting components, but they are also essential parts of many other components, such as MMI-couplers, Star Couplers, Optical Phased Arrays, Arrayed Waveguide Gratings and Mach-Zehnder Modulators. In the foundry platforms of SMARTPhotonics and HHI a few types of waveguide are available: shallow and deep etched waveguides, isolation sections, and waveguide bends. In this chapter we will briefly describe them and their most important properties: propagation loss (absorption and scatter loss), radiation loss in bends, birefringence, electrical resistance and fabrication tolerance.

9.1 Waveguide structure in the TU/e - SMART Photonics process

The layer structure of the waveguides cannot be modified by the user. It is defined by the foundry and is chosen such that the waveguide is transversely single mode. The width and the shape of the passive waveguide structure can be defined by the user and this enables the design of a wide range of components, as described in the following chapters.

Figure 9.1 shows the transverse structure of the TU/e waveguide structure, which closely resembles the waveguide structure of the SMART Photonics foundry. Two different waveguide types are available: shallow-etched waveguides, which are etched 150 nm into the quaternary waveguide layer, and deep-etched waveguide which are etched 100 nm through the quaternary waveguide layer. The shallow waveguides have the advantage of lower scatter losses because of the lower lateral effective index contrast. Their radiation loss in waveguide bends is higher, however, because of the low contrast and, consequently, their minimum bending radius is larger, in the order of 150 μm . Deep etched waveguides support much smaller bending radii, smaller than 25 μm , but their scattering losses are higher, in the order of 1 dB/cm with good lithography and etching. For shallow waveguides the scattering loss can be significantly below 1 dB/cm.

Figure 9.2 shows a SEM-photograph of a passive waveguide structure, including an

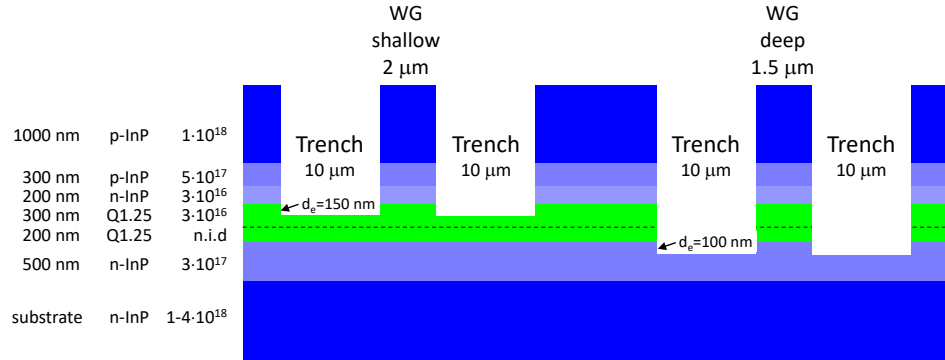


Figure 9.1: Waveguide structure in the TU/e SMARTPhotonics platform

MMI-coupler with two input tapers and curved ridge-waveguides. The whole waveguide structure is embedded in a trench. Outside the trench we see a pattern of tiles, which has been included in order to avoid large differences in etching conditions between the etched and non-etched regions. The filling ratio of the tile pattern is chosen such that the local non-uniformity of the etch rate is minimal. Without such a pattern the etch-rate at the edge of a non-etched region will be significantly larger than farther away from the edge. See Sec. 9.2, lag-effect.

9.2 Waveguide modes

Figure 9.3 shows the intensity profiles of the guided modes in the standard shallow and deep etched waveguides of the SMART Photonics foundry platform. Vertically all waveguides are single mode, they guide the fundamental TE and a TM modes. In the lateral direction the shallow ridge waveguides also guide a first-order mode. This means that designers have to be careful with the design of their circuits not to excite first-order modes. This may happen at asymmetric discontinuities in the waveguide, for example at junctions between straight and curved waveguides. In waveguide bends with a small bending radius the first order mode will experience high loss, so bends will act as mode filters. Another way to get rid of first order mode contamination is by applying MMI mode filters (see Sec. 19.5).

For the deep etched waveguides the first order lateral modes are cutoff. Further we see that the effective indices of the TE- and the TM-mode are very close. At a width of 1.49 μm they are almost equal and for smaller widths the TM_{00} -mode has a higher index than the TE_{00} -mode. So at this width the waveguides behave almost polarisation independent. However, as explained in Sec. 9.5 waveguide width window in which the waveguide is polarisation independent is very narrow and fabrication intolerant.

9.3 Waveguide propagation loss.

The propagation loss of a passive waveguide is usually expressed in dB/cm and sometimes in cm^{-1} . The two are related according to

$$A[\text{dB}/\text{cm}] = 10 \log e^{-\alpha[\text{cm}^{-1}]} = 4.343 \alpha [\text{cm}^{-1}]. \quad (9.1)$$

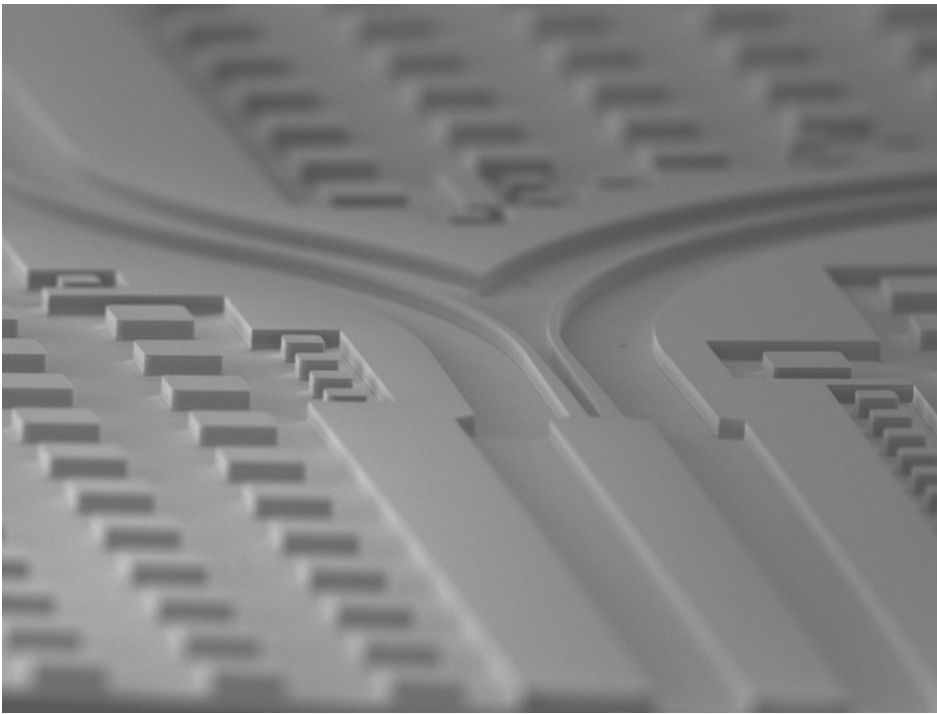


Figure 9.2: Waveguide structure in the SMARTPhotonics platform (SEM-photograph SMART Photonics).

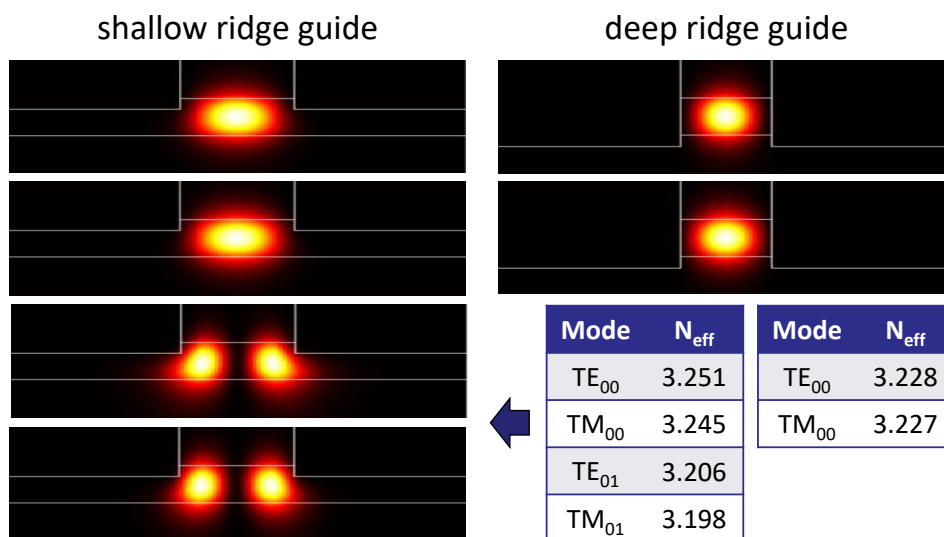


Figure 9.3: The guided modes in standard shallow and deep etched waveguides.

Table 9.1: Bulk loss of the layers of the standard TU/e waveguide and their contribution to the propagation loss.

Material	Thickness	Doping	n	κ	L_{bulk} (dB/cm)	ΔA_{TE} (dB/cm)	ΔA_{TM} (dB/cm)
Ti	200		3.782	4.42	10^6	0.0	0.0
p-InGaAs	300	$1.5 \cdot 10^{19}$	3.74	0.29	10^5	0.0	0.0
p-InP	1000	$1 \cdot 10^{18}$	3.17	$2.8 \cdot 10^{-4}$	100	0.5	0.7
p-InP	300	$3 \cdot 10^{17}$	3.17	$8 \cdot 10^{-5}$	30	0.9	1.1
n-InP	200	$3 \cdot 10^{16}$	3.17	$4 \cdot 10^{-7}$	0.1	0.0	0.0
n-Q1.25	500	$6 \cdot 10^{16}$	3.36	$7 \cdot 10^{-7}$	0.25	0.2	0.2
n-InP	500	$3 \cdot 10^{17}$	3.17	$4 \cdot 10^{-6}$	1	0.2	0.2
n-InP	500	$3 \cdot 10^{18}$	3.17	$3.6 \cdot 10^{-5}$	10	0.1	0.1
SI-InP	substrate		3.17	0.0	0	0.0	0.0
Waveguide loss total						1.9	2.3

The most important contributions to the propagation loss are the loss due to doping, and the scattering loss due to micro-scale roughness of the waveguide edges.

9.3.1 Doping loss

Doping introduces free carriers in the waveguide material, and these can be excited to a higher energy level by absorbing a photon, thus causing propagation loss. Holes have a stronger interaction with photons than electrons and, consequently, p-type material is more lossy than n-type material.

Table 9.1 shows the layer structure of the standard waveguides in the TU/e platform, which closely resemble the layer structure of the SMART Photonics foundry platform. Although the absorption of the metal layers and the InGaAs contact layer is very high, their contribution to the propagation loss of the fundamental waveguide modes is small, because they are sufficiently isolated from the waveguide layer by the 1500 nm InP top layer.

From the table we see that the p-doped InP top layers have a significant contribution to the modal propagation loss. The high doping level of these layers keeps the electrical resistance between the metal contact and the waveguide layer low. This is important to keep the electrical heat dissipation in SOAs and lasers low, and it is also important for high-speed modulators, where the bandwidth is determined by the RC-time. We see that the loss contribution of the n-doped layers is significantly smaller, almost a factor of 10 for the same doping level, so it is important to keep the p-doped layers farther away from the waveguide layer as the n-doped layers. This is the reason that in the standard layer stack there is a low-n-doped InP-layer of 200 nm between the waveguide and the first p-doped layer. The whole design is a compromise between electrical resistance and optical propagation loss.

The lower row of the table shows the total modal loss of the standard (slab) waveguide due to dopant; the propagation loss is in the order of 2 dB/cm, and slightly higher for TM-polarized than for TE-polarized modes, because the former are a bit less confined and experience higher loss from the p-doped cladding. The numbers in the table

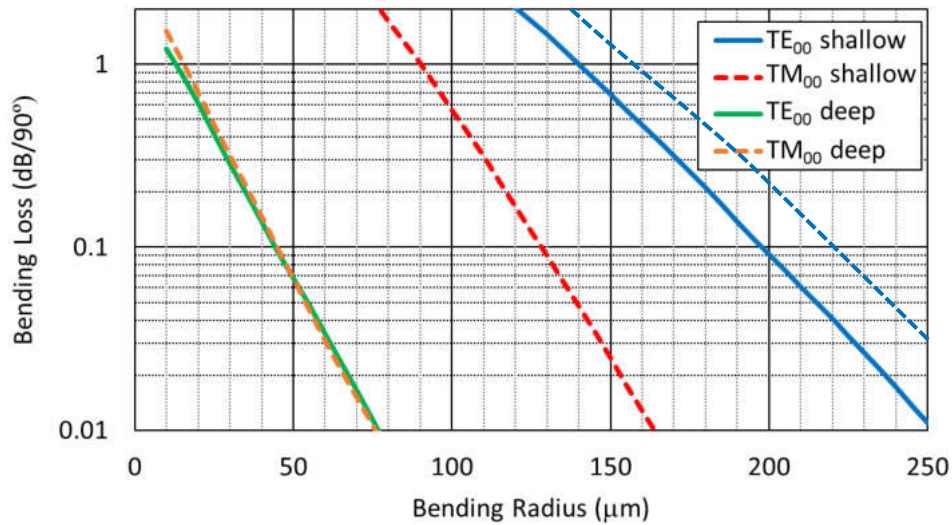


Figure 9.4: Bending Loss for shallow and deep etched waveguides.

are indicative, they are strongly dependent on the doping levels, which can have significant variation from run to run. They illustrate that in a good waveguide etching process doping is the main source of propagation loss.

9.3.2 Scattering loss

In a good waveguide lithography and etching process the scattering losses can be small, typically smaller than 0.2-0.3 dB/cm for shallow-etched waveguides, and smaller than 0.5 dB/cm for deep-etched waveguides. In the standard waveguide structure the scatter loss is significantly smaller than the doping loss. For applications that require low propagation loss, such as long delay lines or high-quality ring filters, it is important to reduce the doping level, especially on the p-side. This requires adaptations from the standard foundry process, however.

9.4 Bending loss

Radiation loss. As described in Chapter 2, section 2.6.4 on page 2-62, bending of the waveguides introduces radiation loss. Figure 9.4 shows the calculated bending loss for standard shallow and deep etched waveguides. It is expressed in dB/90°. For shallow etched waveguides the bending loss is strongly dependent on the etch depth. The curves labeled shallow –50 nm show how the bending loss increases if the etch-depth is reduced with 50 nm to 100 nm into the quaternary layer. On the 1500 nm InP top-cladding layer thickness, 50 nm is only 3%. Such a variation can easily occur and we, therefore, advise to choose the bending radius of shallow waveguides not smaller than 250 μm. For deep etched waveguides, the dependence of the radiation loss on the etch depth is less, because the etch is completely through the waveguide layer.

Mode mismatch loss. In a curved waveguide the mode shifts to the outer side of the bend and it is also compressed. Figure 9.5 on page 9-6 shows how the mode profile changes with increasing curvature c . The red curve shows the mode profile in a straight

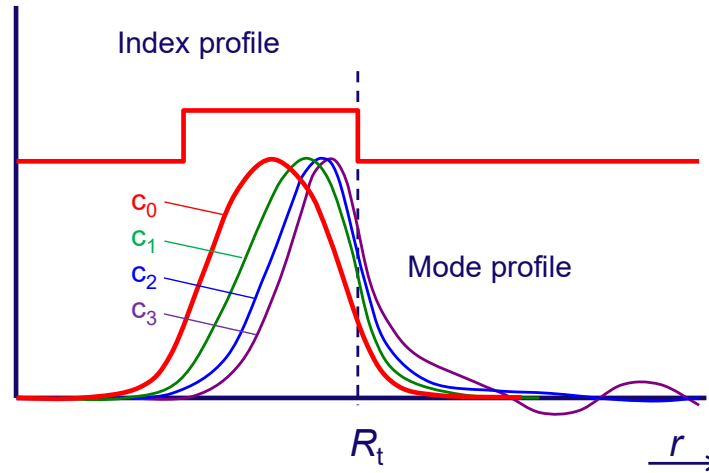


Figure 9.5: Mode profile of the fundamental mode in a curved waveguide for 4 different values of the curvature ($c_0 = 0$: straight waveguide).

waveguide ($c_0 = 0$). If the waveguide is curved the mode starts radiating. For small curvature (c_1) the loss is still small, but the deformation of the mode profile can be such that a significant mismatch loss occurs at the junction between the curved and a straight waveguide. In order to reduce this loss the width and offset of the straight waveguide should be optimized at the junction, as described in Chapter 10. For large curvatures (c_2 and c_3) the radiation loss becomes impractically high.

9.5 Polarisation dependence

Shallow waveguide. In Fig. 2.34 on page 2-51 we see the standard shallow etched waveguide with $2 \mu\text{m}$ width has a significant birefringence:

$$\Delta N_{\text{TE, TM}} = N_{\text{TE}} - N_{\text{TM}} \approx 5.5 \cdot 10^{-3} \quad (9.2)$$

This will lead to polarisation dependent behavior of components which are based on optical length differences, such as Mach-Zehnder Interferometer or ring filters.

Deep etched waveguide. The $1.5\text{-}\mu\text{m}$ -wide deep-etched waveguides are (almost) polarisation-independent. As we can see from Fig. 2.34 on page 2-51 the effective indices for TE and TM are almost identical for this waveguide width (the polarisation independent width is $1.487 \mu\text{m}$) However, their dependence on the waveguide width is different:

$$\frac{d\Delta N_{\text{TE, TM}}}{dw} \approx 0.01/\mu\text{m}. \quad (9.3)$$

This means that a width variation of $0.1 \mu\text{m}$ will lead to a birefringence of 10^{-3} , which is too large for many practical polarisation-independent applications. To keep the birefringence $< 10^{-4}$ requires a waveguide width control of 10 nm , which is very tough.

Problem 9.1: Wavelength shift caused by waveguide width deviation.

Problem: Estimate the shift of the wavelength response of a PIC caused by a deviation Δw of the waveguide width in the standard shallow etched waveguide as described in Appendix C and problem 2.18.

Solution: The wavelength response of a PIC is dependent on the optical length βl , in which $\beta = 2\pi N_{\text{eff}}/\lambda_0$. A change $\Delta\beta$ in β can thus be countered with a wavelength change $\Delta\lambda_0 = -\frac{d\lambda_0}{d\beta} \cdot \Delta\beta$. The change in β due to a deviation Δw of the waveguide width follows as $\frac{d\beta}{dw} \cdot \Delta w$. With $\beta = \sqrt{N_1^2 k_0^2 - k_x^2} \approx N_1 k_0 \left[1 - \frac{1}{2} \frac{k_x^2}{N_1^2 k_0^2} \right] = N_1 k_0 \left[1 - \frac{\lambda_0^2}{8N_1^2 w^2} \right]$ we find $\frac{d\beta}{dw} = N_1 \frac{2\pi}{\lambda_0} \frac{\lambda_0^2}{4N_1^2 w^3} = \frac{\pi\lambda_0}{2N_1 w^3} \approx 0.09$ (with $w = 2 \mu\text{m}$, $N_1 \approx 3.25$ and $\lambda_0 = 1.55 \mu\text{m}$). With $\lambda_0 = \frac{2\pi N}{\beta}$ we find $\frac{d\lambda_0}{dw} = -\frac{2\pi N}{\beta^2} \cdot \frac{d\beta}{dw} = -\frac{\lambda_0^2}{2\pi N} \cdot \frac{d\beta}{dw} = -\frac{1.55^2}{20} \cdot 0.22 \approx 0.01$ and $\Delta\lambda_0 \approx 0.01\Delta w$.

9.6 Electrical properties. Isolation section.

9.7 Fabrication tolerance

Waveguides are used in many components and circuits. In wavelength-selective devices, such as Mach-Zehnder Interferometer filters and ring filters, the wavelength response is dependent on optical length differences $\beta\Delta L$ for the fundamental waveguide mode. Because β is dependent on the waveguide width the wavelength response will also depend on the waveguide width. For the standard shallow etched waveguides we can derive the following dependence of the wavelength shift $\Delta\lambda_0$ on a deviation Δw of the waveguide width (see Problem 9.1)

$$\Delta\lambda_0 \approx 0.01\Delta w$$

The standard deep etched waveguides have a stronger dependence on waveguide width deviations: $\Delta\lambda_0 \approx 0.02\Delta w$. So for a shallow etched waveguide a 10 nm reduction of the waveguide width causes a wavelength shift of 0.1 nm, which corresponds to about 12.5 GHz, and 25 GHz for the deep etched waveguides.

40 nm waveguide width variation causes a 1 nm wavelength shift of the response.

9.8 PDK-module