Optimization of a layerstack for InP photonic integrated passive components with low-loss and enhanced grating couplers

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Abstract : Generic InP photonic integrated circuits (PICs) allow the integration of passive and active building blocks monolithically. However due to the presence of dopants required for active components, propagation losses of the passive ridge waveguide are usually on the order of 3 dB/cm. Here we propose an optimized layerstack for the passive building block which should allow to reduce propagation losses to 1.27dB/cm for ridge waveguide. This optimized layerstack also adds a thicker grating layer allowing diffractive structures with higher efficiency per unit length as compared to standard generic InP PIC layerstack, enabling millimeter long gratings suitable for chip-to-free space coupling.

Introduction

Integrated photonics has demonstrated on-chip capability for light detection and ranging (LiDAR) applications [1]. For LiDAR, a receiver with high sensitivity is needed in order to achieve long range detection. It is thus of high interest to minimize the propagation losses arising during light transport to the on-chip receiver. Another way to increase receiver's sensitivity is to increase the size and efficiency of the light collection area. Light collection can be done in two ways : through edge coupling or surface gratings couplers. One of the main advantage of surface grating couplers is the ease for increasing the size of the light collection area in two dimensions compared to edge coupling which is limited to the edge plan of the chip (only one dimension).

For the InP photonic platform, grating couplers are usually not exploited due to the weak index contrast between core and top cladding leading to mm long gratings with inefficient coupling to single-mode optical fibers. However, for certain LiDAR functionalities, this can be an advantage, allowing low beam divergence diffraction and large collection areas [2]. In this paper, we are simulating an optimized layerstack for InP photonic integrated passive devices (Figure 1, Low loss layerstack), enabling low loss and enhanced grating strength in the C band wavelength range.

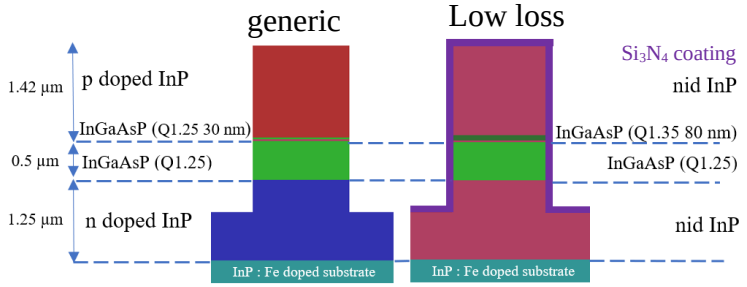

Figure 1 : comparison between generic InP waveguide (left) and low loss, grating enhanced optimized layerstack (right). Note that Q mean quaternary alloy and following number define the wavelength value of the material bandgap.

The first part of this paper will be focused on reduction of propagation losses by minimization of doping level and addition of a thin film coating. The second part will develop the simulation result of grating coupler layer and optimization of different parameters enabling 80% light outcoupling for a 1.6 mm long surface grating coupler.

Waveguide propagation Losses

In integrated waveguide, propagation losses mainly comes from two sources: sidewall roughness producing scattering losses, and free carrier absorption (FCA) coming from intra-band non-radiative absorption. Simulation of free carrier absorption for p and n dopant have been done in this study, relying on the model presented in the appendix of [3]. From Figure 2, it can be seen that to reduce free carrier absorption losses to zero, decreasing the doping level from 1^{18} to 1^{15} cm^{-3} is needed for p dopant and to at least 1^{16} cm^{-3} for n dopant. However in practice it is preferable to have low well-controlled doping level for both dopant in passive devices to avoid any electrical leakage between active and passive devices. Considering this, the choice as been made to use a doping concentration of 1^{15} cm^{-3} for both dopant.

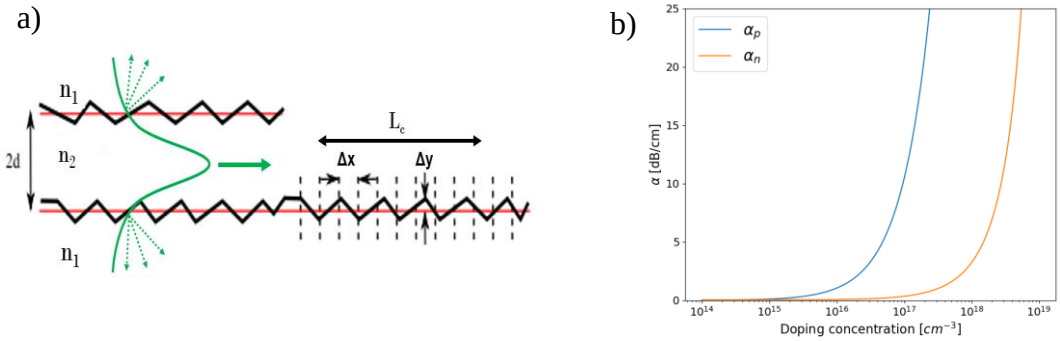

Figure 2 : a) Illustration of scattering losses in integrated waveguide. b) Calculated loss coefficient for p and n doped InP assuming 100 % electric field confinement in the layer.

The second part of the propagation losses are coming from scattering losses. For this, the losses have been studied in two ways. First, using the Payne and Lacey model [4], scattering losses have been simulated using a bulk index cladding n_1 equal to 1.45 (corresponding to SiO_2) with the following equation : $\alpha = \frac{\sigma^2}{\sqrt{2}k_0 d^4 n_1} g(V) f(x,y)$, where α is the loss in m^{-1}, σ is the root mean square value of the sidewall roughness in m, k_0 the wave vector, d the waveguide width in m and n_1 the cladding index surrounding the waveguide. g and f are variables depending on the waveguide geometry detailed in [4]. Yap et al. showed that by multiplying the previous equation by a scaling factor S, it was possible to account for the difference between ridge and rib waveguide [5]. This S factor can be seen as the difference of variation between the index of a ridge and a rib waveguide in function of the width of the waveguide. In other word : $S = \frac{\delta n_{rib}}{\delta n_d} / \frac{\delta n_{ridge}}{\delta n_d}$, where S = 1 if we consider a ridge waveguide. Using the low loss layerstack shown in Figure 1, we have found S equal to 0.54. From the Payne and Lacey model, we can deduce that there are two ways to reduce the scattering loss of a waveguide without modifying its geometrical parameter. First, the reduction of sidewall roughness itself induce a reduction of scattering loss. Second, it is possible to increase the cladding index, in order to decrease the index contrast between sidewall and cladding, leading to a decrease of losses. To keep the bending radius of generic waveguide unchanged, one option is to use thin film coating

in order to locally reduce sidewall roughness and create a smooth transition between waveguide core and cladding using the same concept as shown in [6].
In order to visualize the impact of a silicon nitride thin film coating on losses, a simulation has been done using the 3D FDTD solver of Lumerical. In this simulation, InP and InGaAsP index used at a wavelength of 1.55 µm were respectively 3.167 and 3.372, at a wavelength of 1.55 µm. For both interface, the sidewall roughness value σ was set to 5 nm and the correlation length Lc to 50 nm, relying on values previously measured in [3]. Results obtained from those simulation indicate that by depositing a 100 nm coating of silicon nitride, it should be possible to reduce scattering losses from 1.61 to 1.27dB/cm for a 1.5 µm wide ridge waveguide.

Grating Strength enhancement

As discussed in the introduction, increase the size and efficiency of the light collection area is another important aspect in a LiDAR receiver chip. In the InP generic platform, gratings are etched on a 30 nm thick layer of $In_{0.75}Ga_{0.25}As_{0.55}P_{0.45}$ (Q1.25) [7], see Figure 1 (generic layerstack).**Erreur ! Source du renvoi introuvable.** To further increase the grating strength, there are two options: increase the index of the layer by modifying the layer composition or increase the thickness of the grating layer.
For the grating fabrication, an ArF deep ultra violet (DUV) scanner is used, allowing a minimum feature size of around 100 nm, which has been chose to be the maximum thickness value of the grating layer in order to keep a ratio thickness/width of grating minimum feature size less than 1, avoiding regrowth issues. Next, Tanguy model [8], [9] has been used to determine the refractive index of $In_{1-x}Ga_xAs_yP_{1-y}$.

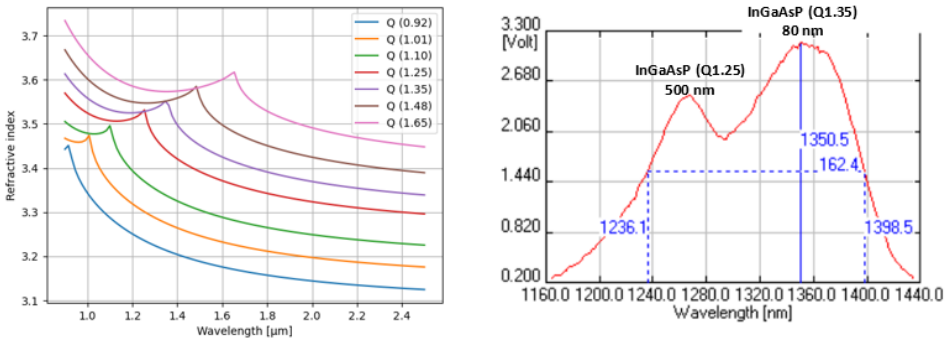

Figure 3 : a) Calculated refractive index and b) measured photoluminescence of an InP wafer grown with 500 nm of Q(1.25) and 80 nm of Q(1.35) on top of it.

From Figure 3, we can deduce the refractive index of the InGaAsP Q1.25 and Q1.35 layer which are respectively 3.372 and 3.342. Q1.35 is chosen by assuming that after 150 nm from the bandgap wavelength, absorption of the material has fallen to zero, leading to zero absorption around 1500 nm (based on the case of Q1.25 absorption at 1.4 µm).
Finaly, an efficiency of 80% light out of the grating after a length of 1.6 mm has been chosen for the receiver in order to have a tradeoff between large collection area and integration with the rest of the on-chip receiver circuit. By simulating the grating coupler in a 2D FDTD simulation, it is then possible to determine the grating strength by taking the power curve of light transmitted on top of the grating and fit it with a curve of the shape $Ae^{-2\alpha z}$. In this equation, A is the initial intensity inside the waveguide, α is the grating strength in m^{-1}, z is the length of the grating simulated in m and the factor 2 takes into account the fact that approximately the same amount of light is sent on top and on bottom of the simulated grating.

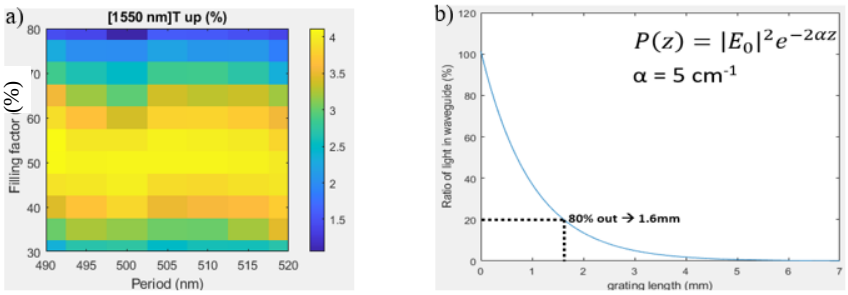

Figure 4 : a) Ratio of light transmitted on top of the grating after 90µm for different filling factor and b) grating strength extracted for a grating with a filling factor of 50%, a period of 505 nm and an InGaAsP (Q1.35) grating layer thickness of 80 nm. Wavelength used for simulation was 1.55 µm.

Figure 4 indicate that using a 80 nm thick InGaAsP (Q1.35) layer, it is possible to obtain 80% of light out of the waveguide in a 1.6 mm long grating. It has to be noted that those 80% are in reality almost twice the collection efficiency of the grating because about half of the light is sent on the bottom of the grating. This implies that half of the light will not be collected in the waveguide but will goes into the substrate, leading to a collection efficiency of around 40%.

Conclusion

A low loss waveguide with enhanced grating strength has been proposed and simulated. By decreasing the p and n doping level it is possible to remove free carrier absorption. Moreover, by adding a 100 nm layer on top of a 1.5 µm wide waveguide, scattering losses can be reduced from 1.6 to 1.27 dB/cm for a roughness of 5 nm and a correlation length of 50 nm. We expect even higher reduction compared to non-coated waveguide for higher roughness. Lastly, by modifying the grating layer composition from InGaAsP (Q1.25) to InGaAsP (Q1.35) and increasing its thickness to 80 nm, the grating strength has been increased up to 5 cm^{-1}, allowing on-chip mm long efficient light out/in coupling.

References

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