1955

Optical Design of a Novel Wide-Band Membrane Electro-Absorption Modulator Based on Bandfilling

J. P. van Engelen,[1] L. Shen,[1] G. C. Roelkens,[1,2]
Y. Jiao,[1] M. K. Smit,[1] and J. J. G. M. van der Tol[1]

[1] Photonic Integration Group, Eindhoven University of Technology, The Netherlands
[2] Photonic Research Group, Ghent University – IMEC, Belgium

Recently we proposed a novel membrane electro-absorption modulator (EAM) based on the bandfilling induced absorption change in n-InGaAs. We now present the optical design and give a detailed analysis on the extinction ratio (ER) and insertion loss (IL). An improved design is given that results in an ER of 7.9 dB/100μm and an IL of 2.2 dB/100μm. This allows a modulation speed of 15 GHz for a device with a given ER of 7 dB, which makes it suitable for datacom applications.

Introduction

To be compatible with CMOS electronics, optical modulators on silicon require a small driving voltage and a small footprint. Furthermore, to support multipe wavelengh channels, as is envisioned for very high data rates, a wide optical bandwidth is desirable. Modulators based on the quantum-confined Stark effect can be made compact, but have a narrow optical bandwidth. Conventional phase modulators are optically broadband, but their dependence on a Mach-Zender interferometer for intensity modulation leads to a large footprint. Recently we proposed a novel modulator [1] that meets a range of requirements: a compact, optically broadband EAM that can be driven by CMOS electronics. In this paper we first briefly discuss the electrical operation of the modulator for background, then we present an optimized design.

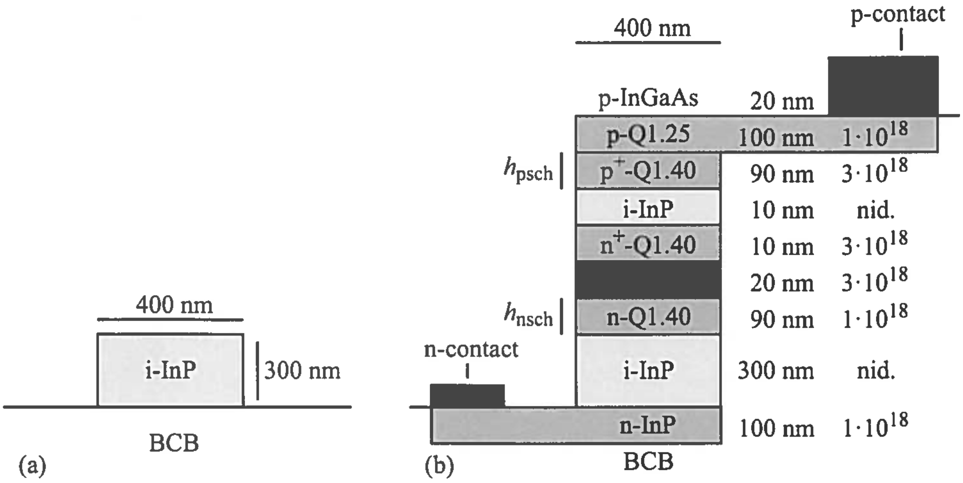


Figure 1: (a) Passive waveguide crosss section. (b) Device structure with layer material, thickness and doping (in cm^{-3}) indicated.

Electrical Design

The modulator is based on the bandfilling effect in highly doped n-InGaAs. At low electron concentrations ($< 5 \cdot 10^{17}$ cm^{-3}) InGaAs is absorbing. At higher electron concentrations, the conduction band fills up and photons require higher energies for absorption to occur [2]. At very high electron concentrations ($> 3 \cdot 10^{18}$ cm^{-3}) absorption is low.

A pin junction is used to modulate the electron concentration in a n-InGaAs layer. This layer is doped at $3 \cdot 10^{18}$ cm^{-3} to be transparent and can be depleted by applying a reverse bias. An intrinsic InP layer is placed between the p and n layers to limit tunneling [3] and avalanching currents.

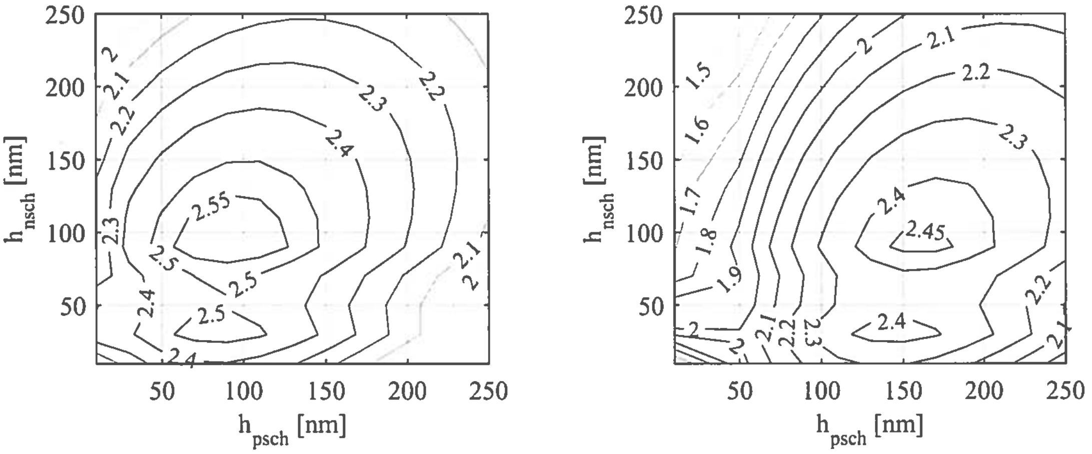
Due to built-in depletion, part of this n-InGaAs layer would normally be absorbing with no applied voltage, leading to insertion loss. Therefore a thin n-Q1.40 layer is introduced between the i-InP and n-InGaAs layer, with the exact thickness of the built-in depletion depth, to reduce this insertion loss.

Semiconductor physics simulation software is used to optimize the doping and thickness of the n-Q1.40 and n-InGaAs layer. The absorption layer is thick enough to neglect quantum confinement.

This pin junction forms the basis of the modulator and is the most important part of the electrical design. In the rest of the paper we will discuss the optical design. It is important to note that we are relatively free to move this pin junction around to maximize the optical performance.

Optical Design

The purpose of this study is to maximize the ER of the device by increasing the overlap of the optical mode with the absorption layer. To make the optical design easier the electrical behavior is simplified. In the modulator's transparent state (no applied voltage), the n-InGaAs layer is assumed to have an electron concentration of $3 \cdot 10^{18}$ cm^{-3}. In the



(a) Fundamental TE mode

(b) Fundamental TM mode

Figure 2: Overlap (in %) of the fundamenal TE and TM mode with the n-InGaAs absorption layer as a function of the height of the p- and n-Q1.40 layers, h_{psch} and h_{nsch} respectively.

absorbing state (-1.5 V) 10 nm of the n-InGaAs is depleted. This leads to a material absorption in the n-InGaAs of 300 cm^{-1} in the non-depleted part and 6000 cm^{-1} in the depleted part [4].

Later in this paper we present a taper design which has low reflection ($< 1\%$) and high transmission (94%) into the fundamental mode of the device. Therefore we can neglect reflections of the interface and beating of modes inside the device.

To increase the ER compared with the previous design [1] the overlap of the optical mode with the n-InGaAs absorption layer needs to be increased. In the design we have a lot of freedom in the position of the absorption layer. We investigated several improvements to the previous design: exchanging the p- and n-contacts; a twin-waveguide structure where all the device layers are either above or below the waveguide layer; introducing layers with high refractive index around the absorption layer.

We use a 2D FDE mode solver to calculate the overlap of the fundamental TE mode with the n-InGaAs absorption layer. The previous design [1] has an overlap of 2.01 %. Exchanging the p- and n-contacts such that the p-contact is below the waveguide and the n-contact at the top of the device increases the overlap to 2.26 %. However this small increase in overlap does not outweigh the cost of many more production steps. The twin-waveguide design gives the highest overlap of the designs: 2.70 %, but also introduces many production steps. The introduction of the high refractive index layers gives an overlap of 2.60 % while not requiring additional production steps. Therefor, to keep the production process simple, the only modification we make is to introduce the high refractive index layers. The design is then as shown in Figure 1.

To optimize the thickness of the newly introduced high refractive index layers we sweep the thickness of these layers, h_{psch} and h_{nsch} (shown in Figure 1). The resulting modal overlap with the absorption layer is shown in the contour plot in Figure 2a. The highest overlap is 2.60 % for a thickness of 90 nm for both n- and p-side layers. In Figure 2b the overlap with the fundamental TM mode is shown with a maximum overlap of 2.46 % for $h_{\text{psch}} = 160$ nm, $h_{\text{nsch}} = 90$ nm. Note that for this point the overlap with the fundamental TE and TM mode is approximately equal, leading to a device with an ER that is polarization independent.

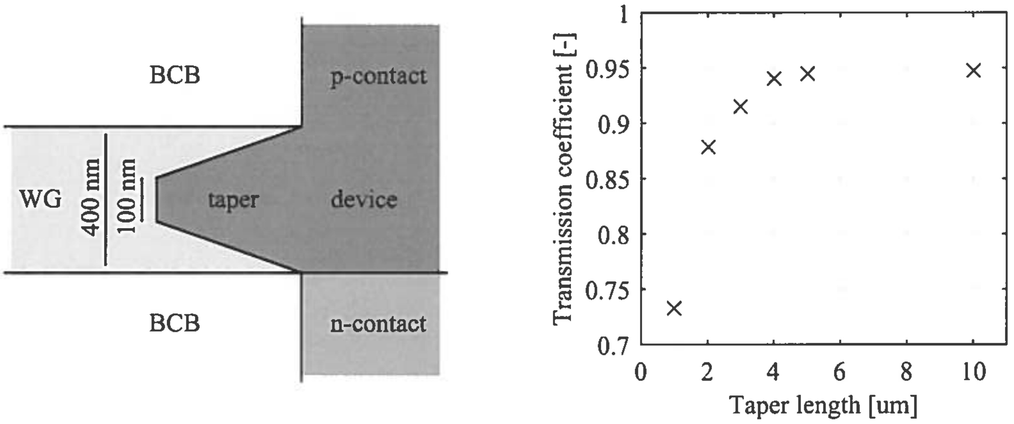
For the device with $h_{\text{psch}}, h_{\text{nsch}} = 90$ nm the mode solver gives a modal loss of 981 dB/cm and 220 dB/cm for the on and off state of the device respectively. This leads to an ER of 7.9 dB/100um and IL of 2.2 dB/100um.

In the previous design the contact layers where close to the n-InGaAs absorption layer causing the polarization of the fundamental TE mode to be angled (the TE fraction of this mode being 74 %). In the new design these layers are further away leading to a TE fraction is 0.97. This makes design of the taper easier as it reduces the chance of beating.

Taper Design

Because the mode in the device has a low overlap with the mode in the passive waveguide, a taper is needed to couple the light to the device. All layers of the device that are above the waveguide layer are tapered in a trapezoidal shape, this is shown in Figure 3a.

A 3D FDTD EM solver is used to determine transmission and reflection of the fundamental TE mode when propagating from the waveguide to the device through the taper. The transmission of this mode to the fundamental TE mode inside the device is shown in Figure 3b as a function of taper length. We choose a taper length of 5 um as longer tapers



(a)

(b)

Figure 3: (a) Top view of taper design, the light propagates from the waveguide through the taper into the device. (b) Transmission of fundamental TE mode in waveguide to fundamental TE mode in the device. A taper length of 5 um is sufficient for a transmission of 94 %.

will not improve the transmission coefficient further. The transmission of the designed taper is 94 % (−0.27 dB) which is sufficient for our application. This leads to a loss of 0.54 dB due to both tapers. Reflection back into the guided modes of the waveguide are under 1 %.

Conclusion

The optical design of a novel EAM based on the bandfilling-effect has been presented. The overlap of the optical mode with the n-InGaAs absorption layer has been increased by introducing high refractive index layers around the absorption layer. This leads to a higher ER. Furthermore a taper design with high transmission and low transmission has been presented. The proposed design is predicted to have an ER of 7 dB and a IL of 2.7 dB for a 90 um long device that has a RC-limited modulation speed of 15 GHz.

References

[1] J.P. van Engelen, "A Novel Optically Wide-Band Electro-Absorption Modulator based on Bandfilling in n-InGaAs", in *Proceedings of the 18th European Conference on Integrated Optics*, 2016.

[2] B.R. Bennett, "Carrier-Induced Change in Refractive Index of InP, GaAs, and InGaAsP", *IEEE Journal of Quantum Electronics*, vol. 26, no. 1, 1990.

[3] J.P. van Engelen, "Modelling Band-to-Band Tunneling Current in InP-based Heterostructure Photonic Devices", in *Proc. of the 20th Annual Symposium of the IEEE Photonics Society Benelux Chapter*, 2015, pp. 27-30.

[4] L. Shen, "Ohmic Contacts With Ultra-Low Optical Loss on Heavily Doped n-Type InGaAs and InGaAsP for InP-Based Photonic Membranes", *IEEE Photonics Journal*, vol. 8, no. 1, 2016.