

# Monolithic Multilayer InP Integration for Large Scale PICs

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*Monolithic multi-layer InP integration can be used to enable three-dimensional connectivity for photonic integrated circuits, offering a step change in optical circuit connectivity. The improved connectivity is required for mesh-interconnection in large-scale switching matrices to avoid losses and crosstalk in the large shuffle networks. This paper focusses on the design of optical vias to couple two vertically separated guiding layers and move light up and down the layer stack. Methods to isolate the waveguide planes from each other are also proposed for reduced interlayer crosstalk.*

## Introduction

Single-layer InP photonic integrated circuits already enable component numbers of up to 1700 for Tb/s class transmitters using nested modulators and multiplexers [1, 2]. However large-scale integrated optical switch matrices require a complex mesh interconnection which is not well supported by single layer waveguides. For switching matrixes, photonic component numbers have been limited to the hundreds on a single chip [3]. Further scaling motivates more sophisticated optical wiring.

A number of dual-layer waveguide methodologies have been proposed to enable 2.5D and 3D photonic integration [4-6], but such implementations have commonly required double sided processing, wafer bonding or combinations of the two approaches. An integrated twin-guide structure has been demonstrated [7] where the active and passive functions are separated into two different vertically displaced waveguides and coupled through long vertical evanescent couplers. In [8], the use of an asymmetric twin waveguide has been proposed, but the use of adiabatic tapers make the design longer and the small (sub-micron) tips are difficult to achieve with a standard lithography. Vertically coupled waveguides have been presented [9] with decoupling between the bottom and top waveguide. To date, dual waveguide techniques have primarily been used to create new types of devices and functions rather than improve interconnection.

In this paper we address the creation of a robust second optical connection layer. We present the monolithic multi-layer InP integration concept using dual width waveguides to allow light routing up and down the layer stack. Short optical vias and long decoupled upper level optical wiring are designed and simulated.

## Optical via

The monolithic multi-layer InP concept includes two vertically-stacked guiding layers. Vertical confinement for the two waveguiding layers is defined by InP cladding layers around an upper and a lower core. The etched layer stack as shown in Fig. 1 includes a top waveguide core comprising three Q1.4 layers with thicknesses 350 nm, 300 nm and 350 nm, separated by two 100 nm InP layers. The spacer layer is 1000 nm thick InP layer. The lower waveguide core is 500 nm thick. The horizontal confinement at the bottom layer evolves along the optical via to guide light up and down the layer stack. To create a lower waveguide connection, the top stack is removed to leave a conventional shallow etched structure (Fig. 1a). To create an upper waveguide connection, the upper

core remains on top and is deep etched with a shallow etched spacer underneath (Fig. 1b). The precise dimensions determine the optical coupling between upper and lower cores. A transition between the lower and higher guiding cores is implemented with the cross-section in Fig. 1c: This is the cross-section for the *optical via*. The waveguide widths defined at the optical via enable phase matching conditions between the two optical cores. The 3-D mode propagation tool, FIMMprop [10], is used to quantify the net transmitted power along the designed component.

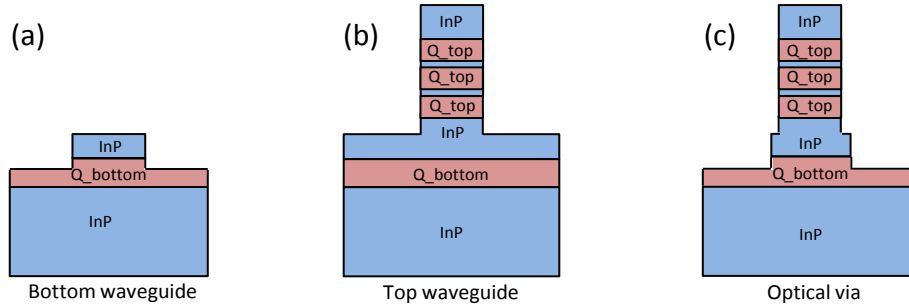


Fig. 1 – Waveguide cross-sections along the propagation plane for (a) the lower waveguide guiding, (b) the upper waveguide guiding and (c) the optical via.

Figure 2 shows the optical via along the propagation plane. The optical via is designed to couple light between the lower core and the upper core. The simulated device in Fig. 2 includes a first 10  $\mu\text{m}$  long input section defined with the lower waveguide only (see cross-section A and guided mode). This is followed by the optical via with a double core structure as shown in cross-section B. This via is then mirrored to provide the reciprocal down-coupling via to couple the light back down to the lower guide.

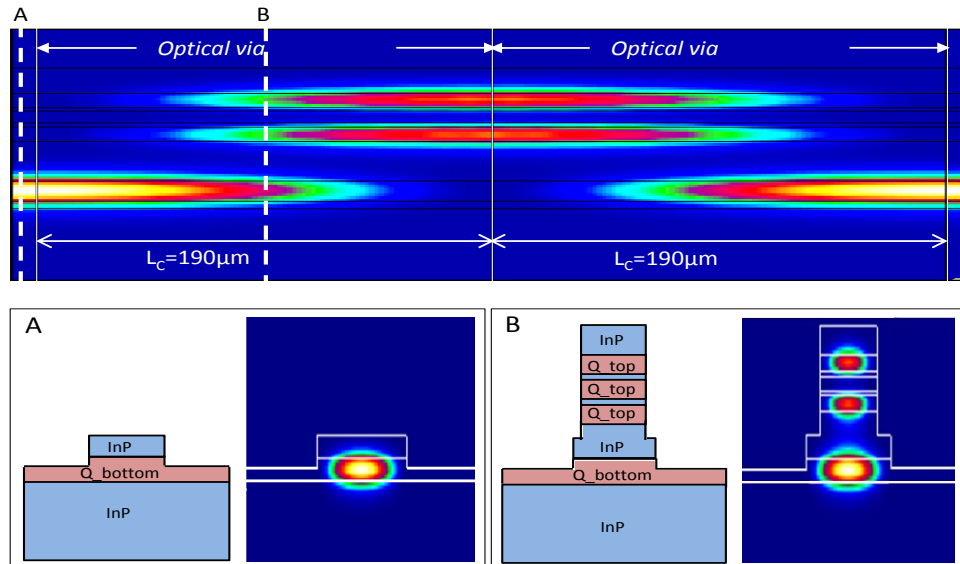


Fig. 2 – Cross-section in the optical plane showing input coupling, two optical vias and output coupling (top) On the bottom left, the intensity mode profile in the lower guide, and in the bottom right, the mode intensity profile at the mid-point of the optical via.

The optical stimulus at the bottom left waveguide is the TE fundamental mode for the lower isolated waveguide. This enters the optical via section exciting super-modes (modes in the cross-section B in Fig. 2): Optimum power coupling of light from the lower guide to the upper layer occurs at a coupling length  $L_c$  which is set to 190 $\mu\text{m}$  in this work. The second optical via couples the light back into the bottom waveguide.

A maximum transmitted power of 98.9% is calculated for a coupling length of  $L_C=190\mu\text{m}$  after the optical power is coupled back into the bottom waveguiding layer (Fig. 3a). When fixing the top waveguide width to  $2.1\mu\text{m}$  and scanning the bottom waveguide width, the optimal coupling is obtained for a  $3\mu\text{m}$  wide bottom waveguide. A maximum transmitted optical power of at least 98% is coupled for a bottom waveguide width value ranging from  $2.9$  to  $3.2\mu\text{m}$  (Fig. 3b).

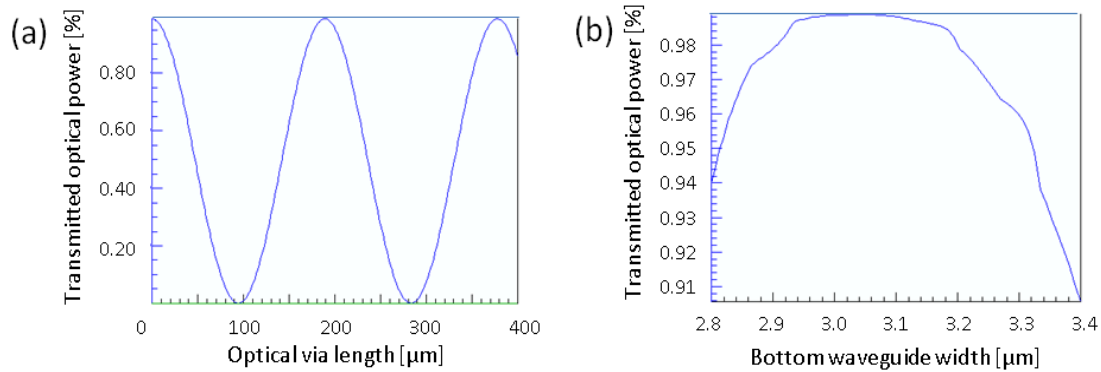


Fig. 3 – Transmitted optical power versus optical via length (a) and bottom waveguide width (b).

### The optical crossing

Once the optical signal is coupled to the top optical wiring plane, it is important to prevent signal leaking back unintentionally into the bottom plane with the optoelectronic devices. A method to isolate the waveguide plane is now presented. The upper core is designed to cross over lower parallel optical cores for maximised integration density. The cores are decoupled by optimising the waveguide width values.

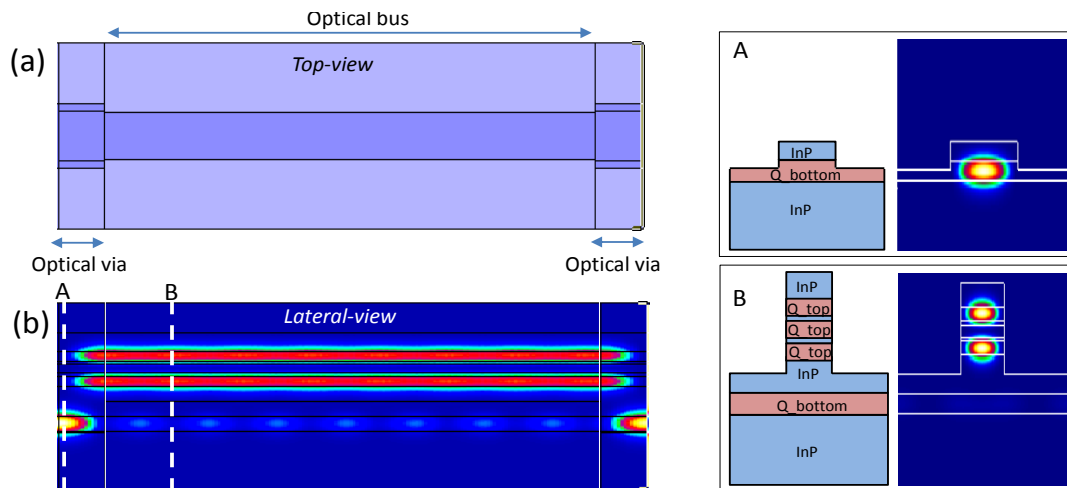


Fig. 4 – (a) Top view of the simulated component including the optical bus and screen-shot of the lateral view of the light propagation.

The design now includes a 2mm long upper waveguide section between the two optical vias (Fig. 4). The cross-sections of the input bottom waveguide and of the top crossing waveguide are shown in Fig.4, together with the guided modes. The worst case transmitted optical power is calculated to be 88% (Fig. 5a). This loss includes 0.05 dB losses from the two optical vias. A small amount of light couples back and forth between the upper and lower cores with a coupling length of  $140\mu\text{m}$  (Fig. 4b): The oscillating behavior shows that the decoupling is imperfect. The upper layer connection

is calculated in presence of fourteen  $2\mu\text{m}$  wide bottom layer crossings placed to study worst case performance. Transmission through the upper layer connection incurs a worst case unoptimised excess loss of  $2\text{dB}/\text{mm}$  (Fig.5b).

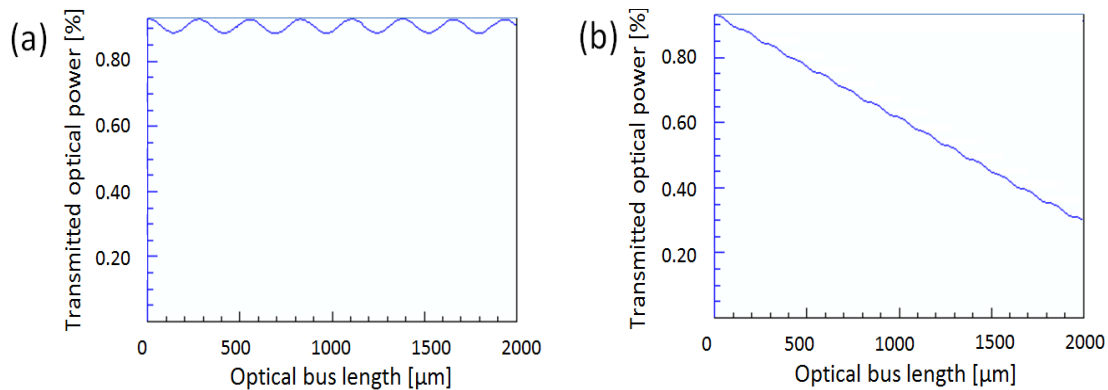


Fig. 5 – Transmitted optical power versus the optical bus length, without (a) and in presence (b) of fourteen waveguide crossings underneath.

## Conclusions

A dual layer monolithically integrated InP concept is proposed comprising short optical vias and long range optical interconnections in a second optical wiring plane. Excess losses of order  $0.025\text{dB}$  are calculated for the optical via and  $2.5\text{dB}/\text{cm}$  for the upper wiring plane only. These components can be used to enable three-dimensional connectivity for a step change in photonic integrated circuit connectivity.

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