Design of Si-Photonic structures and evaluation of their radiation hardness dependence on design parameters

M. Zeiler, S. Detraz, L. Olantera, G. Pezzullo, S. Seif El Nasr-Storey, C. Sigaud, C. Soos, J. Troska and F. Vasey
CERN, Geneva, Switzerland

Introduction

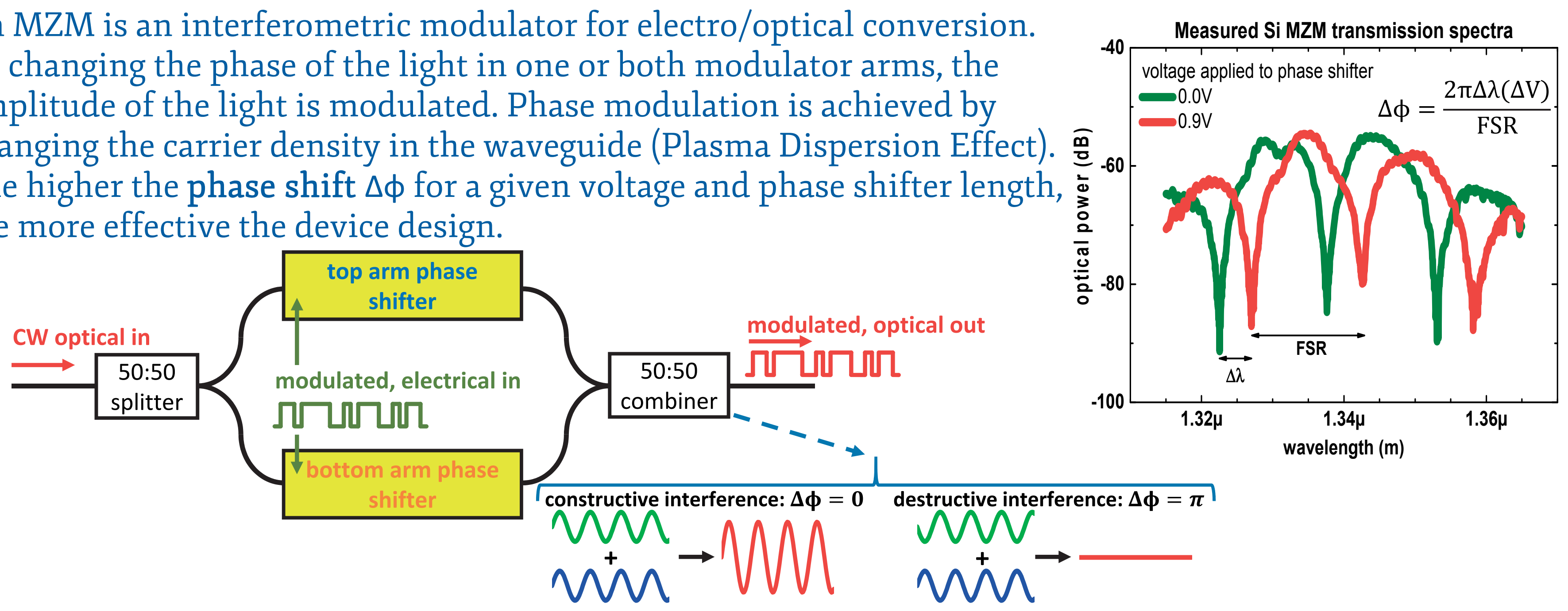
Silicon photonic (SiPh) components can enable new design paths for future optical read-out systems designed for environments with high radiation levels. They potentially offer:

- **High data rates**, wavelength multiplexing
- ➔ Reduced fibre count in detector
- Possibility for **integration or hybridization** with driving electronics and silicon particle sensors
- ➔ Increased chip functionality, decreased assembly costs
- **Radiation hardness** similar to silicon particle detectors (with remote laser source)
- ➔ Positioning of components closer to interaction point, elimination of copper wiring

First results from radiation tests indicate that SiPh Mach-Zehnder modulators (MZM) are almost insensitive to neutron radiation. However, their performance degrades strongly when exposed to x-rays [1]. SiPh MZMs with varied process parameters have been designed to identify a device design with improved resistance against ionizing radiation.

Si-Photonic Mach-Zehnder Modulator (MZM)

An MZM is an interferometric modulator for electro/optical conversion. By changing the phase of the light in one or both modulator arms, the amplitude of the light is modulated. Phase modulation is achieved by changing the carrier density in the waveguide (Plasma Dispersion Effect). The higher the **phase shift** $\Delta\phi$ for a given voltage and phase shifter length, the more effective the device design.



$$\Delta\phi = \frac{2\pi\Delta\lambda(\Delta V)}{FSR}$$

constructive interference: $\Delta\phi = 0$

destructive interference: $\Delta\phi = \pi$

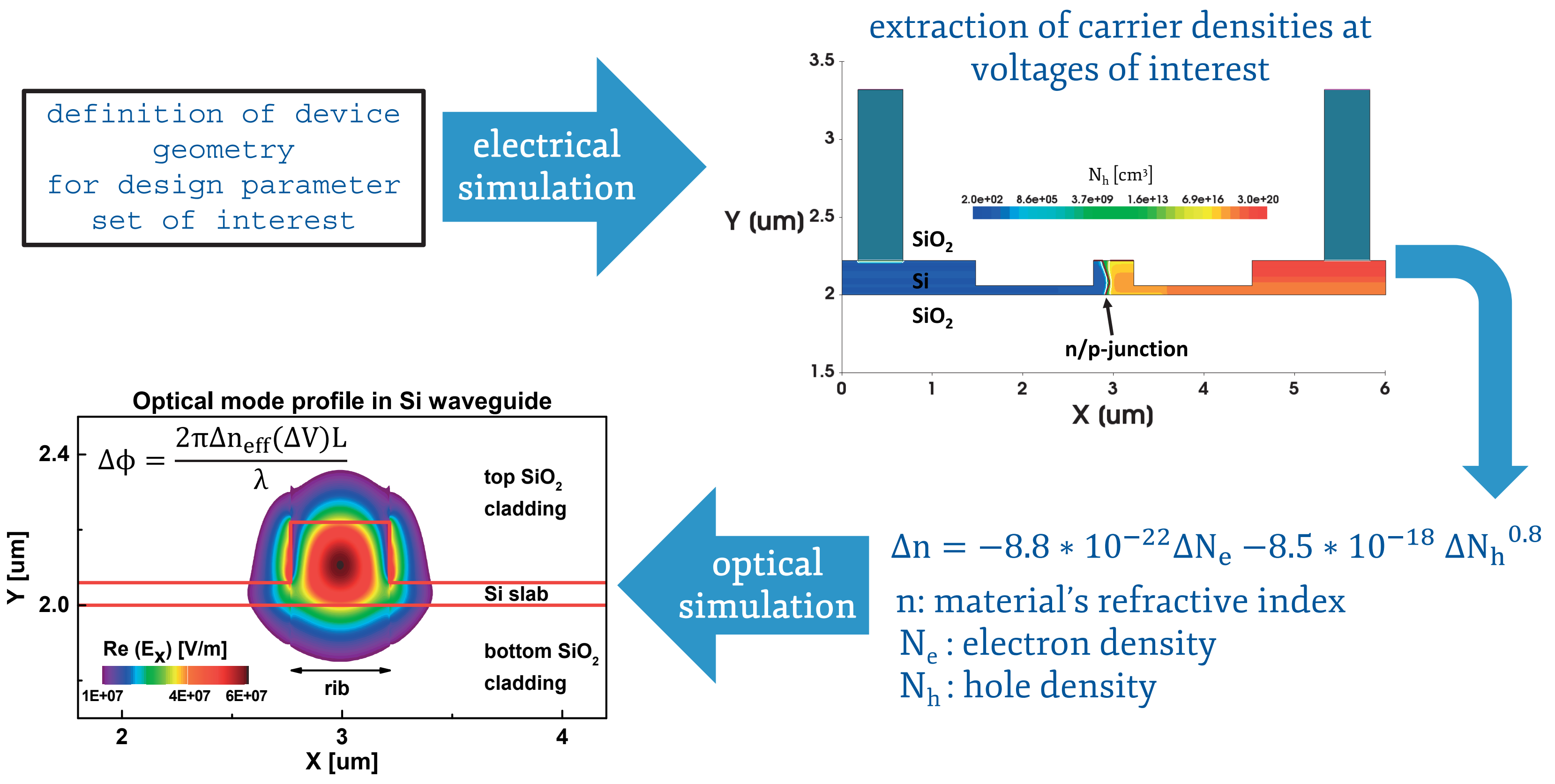
Simulation Method

To ensure the functionality and optimise the efficiency of the custom designed MZMs, the phase shift vs. voltage characteristic has to be simulated. **Steady-state electro-optical simulations** were performed to predict the performance of each potential device design.

The electrical properties, i.e. the free **electron and hole density** in the silicon waveguide as a function of applied voltage, were simulated with the Synopsys Sentaurus TCAD software.

These carrier densities were then converted to a grid of refractive indices. The conversion was done with the empirical formula discovered by Soref and Benett [2].

The **effective refractive indices n_{eff}** and the absorption loss of the guided modes in these silicon waveguides were computed with the PhoeniX OptoDesigner software. The phase shift $\Delta\phi$ for a device of length L and at wavelength λ was then determined based on the change in n_{eff} for a voltage change of ΔV.



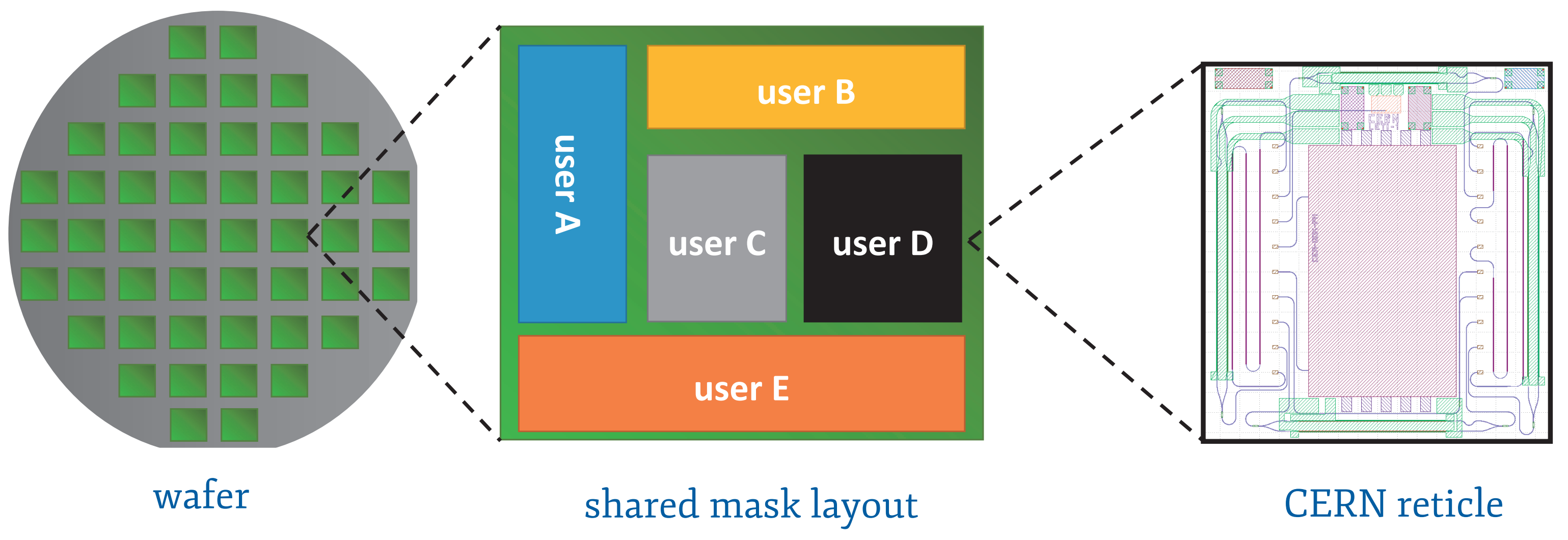
$$\Delta\phi = \frac{2\pi\Delta n_{eff}(\Delta V)L}{\lambda}$$

$$\Delta n = -8.8 * 10^{-22}\Delta N_e - 8.5 * 10^{-18}\,\Delta N_h{}^{0.8}$$

n: material's refractive index
N_e : electron density
N_h : hole density

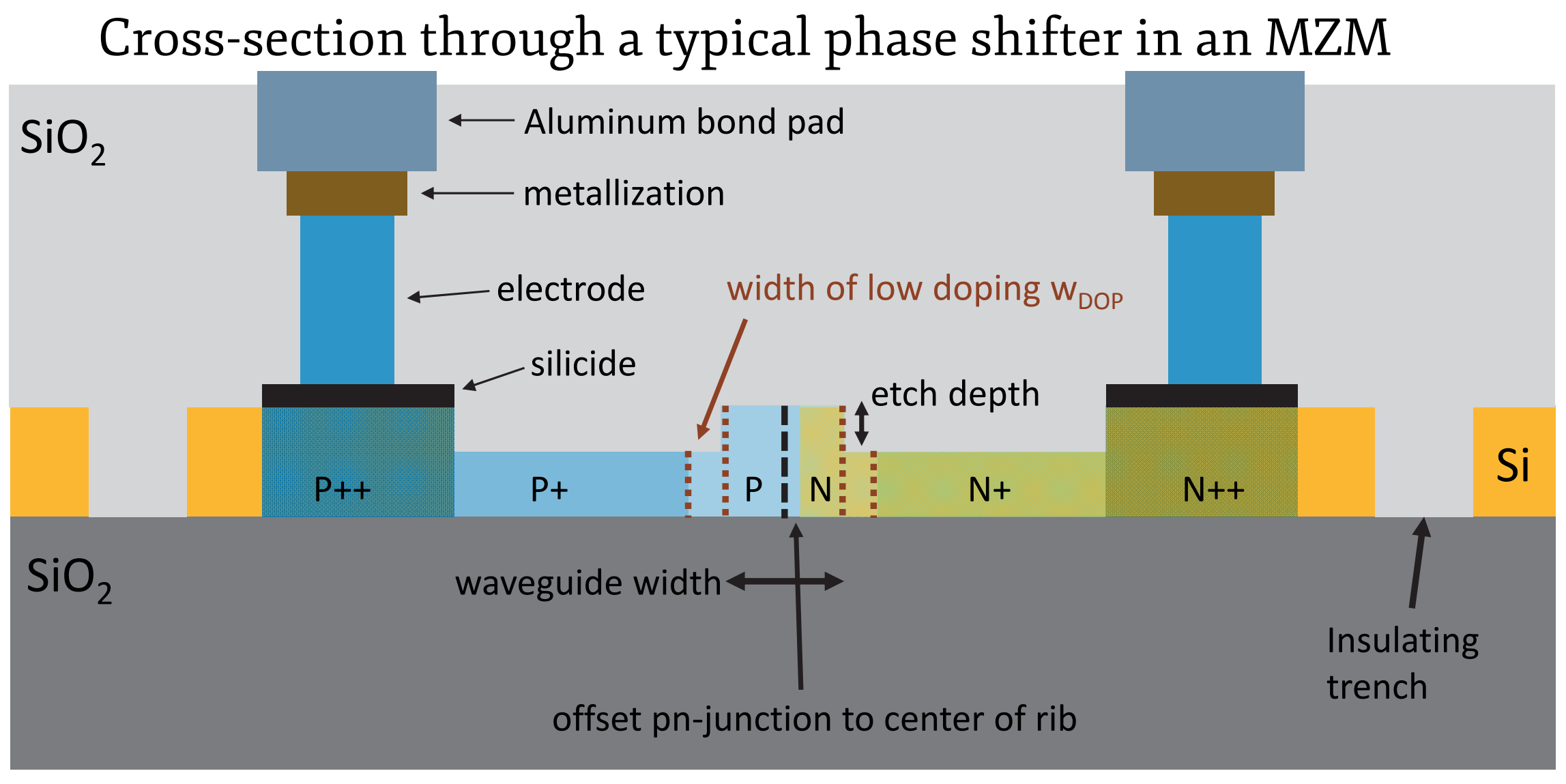
Fabrication

Multi-Project Wafer (MPW) runs, offered through the **ePIXfab** consortium, were chosen for the fabrication of these first prototypes. As the area of a wafer is shared among multiple designs, the prototypes for individual customers become much more affordable. CEA-Leti (France) and imec (Belgium) are the foundries to fabricate the chips.



In order to satisfy as broad as possible a customer base, all fabrication steps in an MPW are pre-defined. Only a very limited number of parameter variations can thus be realised. For our designs these include: etch depths of waveguide, width of low doping region, length of phase shifters, doping concentrations in waveguide.

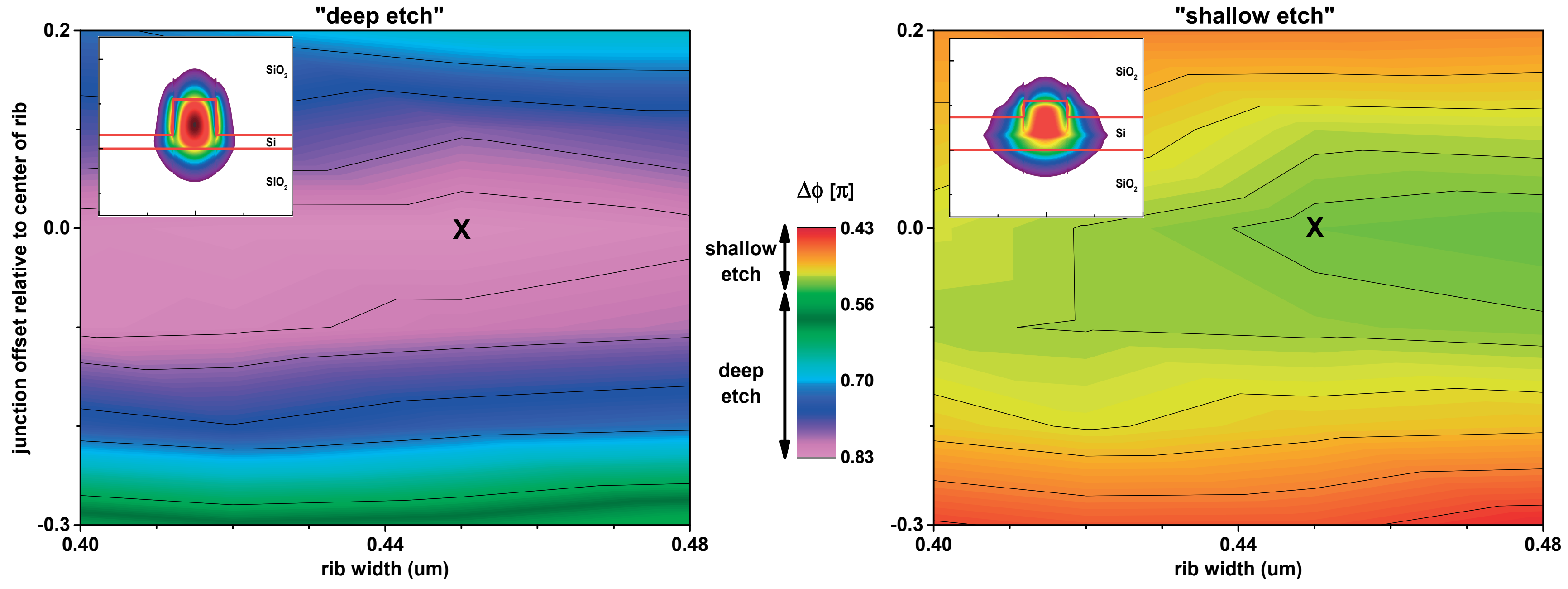
Cross-section through a typical phase shifter in an MZM

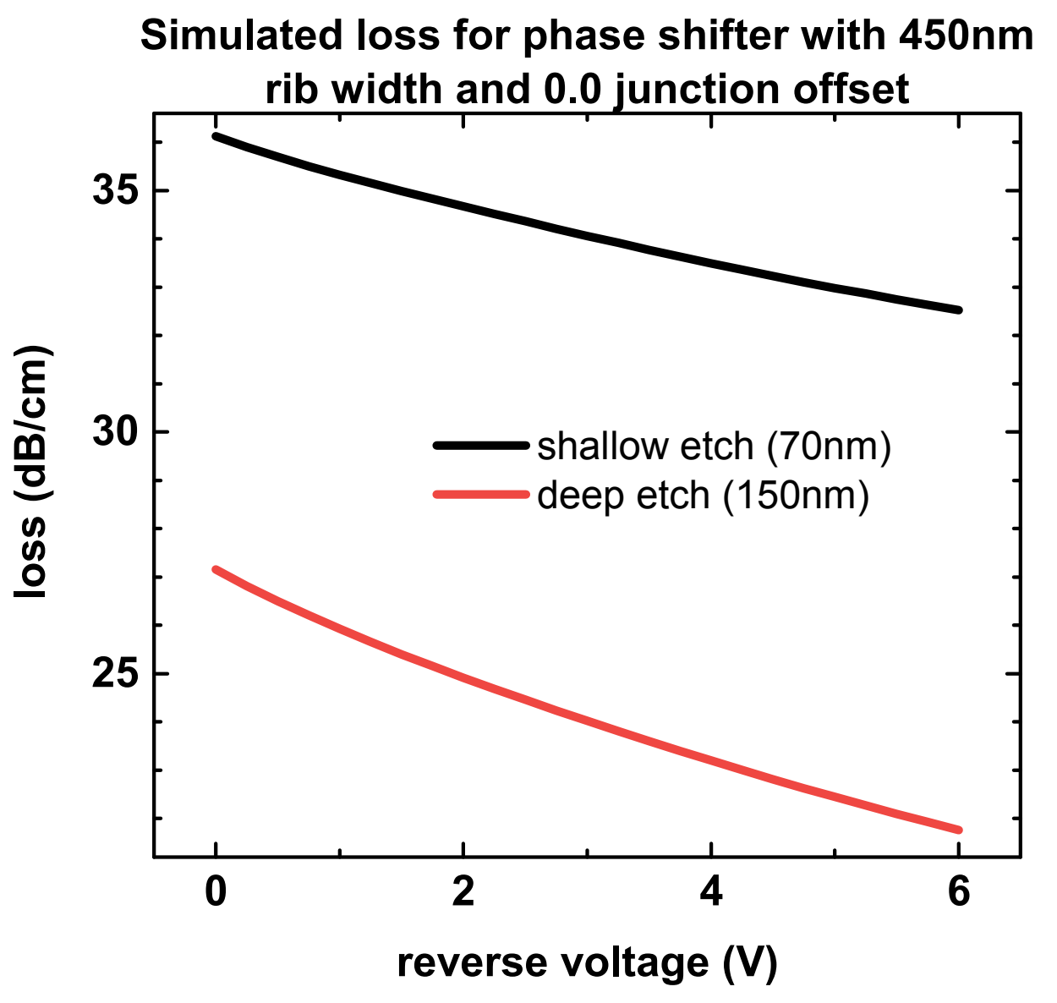


Simulation Results

For an optimised MZM performance, a **large phase shift and low absorption losses** are favoured. Hence, simulations were performed to maximise the overlap of the optical mode and the depletion zone of the pn-junction. In the simulations, the width of the waveguide rib and the offset of the pn-junction relative to the waveguide centre were scanned. Simulation results were produced for both available etch depths. According to these results, a waveguide rib width of 450nm and a junction offset of 0.0 ("X") lead to the best performance in imec's technology. In CEA-Leti's technology, the best performance can be achieved with a waveguide rib width of 450nm and a junction offset of -0.1.

Phase shift for imec waveguide, ΔV=3V, L=4mm



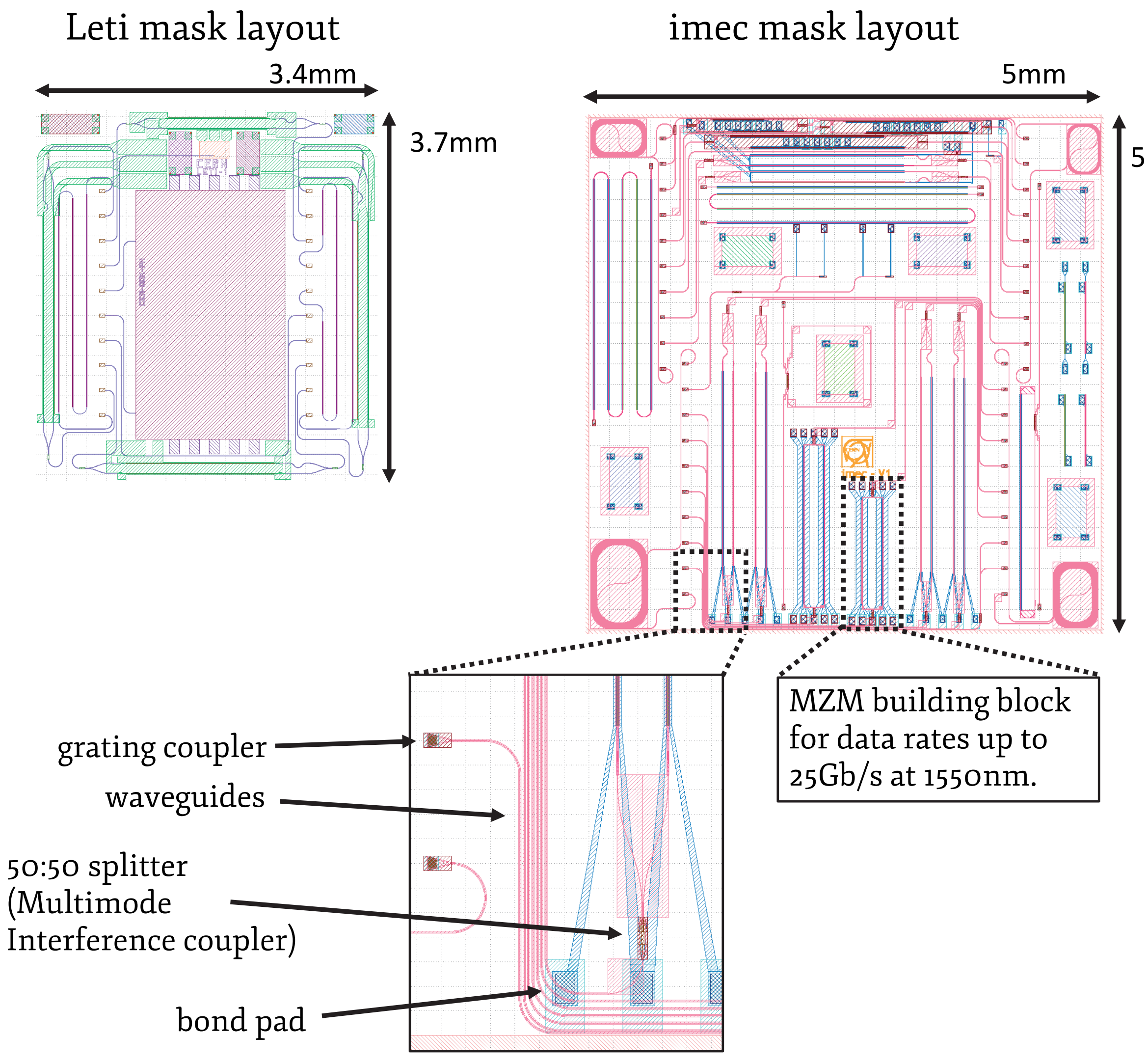


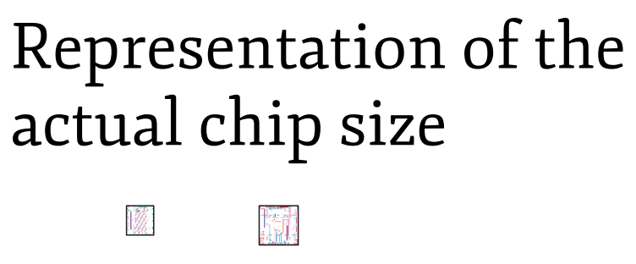
Due to the relatively **high doping concentrations** (1e17-5e18cm³) in the waveguide, the absorption loss in an MZM is usually large. To exclude phase shifter designs that show excessive loss, the guided mode's **absorption coefficient** was determined by a Finite-Difference analysis for the design parameters marked with "X" in the above plots.

As the mode in a "deep etch" waveguide is more strongly confined than in a "shallow etch" waveguide (see insets above), it is less sensitive to doping concentration variations outside the centre of the waveguide rib. The mode in the shallow etch waveguide extends further towards the high doping regions and consequently experiences larger absorption losses.

Fabrication Results

The simulation results were used to define the parameters for custom designed MZMs. The final mask layouts also include photodiodes, various passive test structures and "building-block" devices. Separate mask sets were drawn for CEA-Leti and imec to compare the two distinct processes.





Within an MPW, foundries offer pre-designed components, so-called "**building blocks**", for integration into user designs. Building block grating couplers are used in both mask layouts as an optical interface to the MZMs and passive test structures. Properly arranging the grating couplers, but also the bond pads, is crucial for testing the fabricated chips.

Conclusions

Custom made silicon photonic components are being investigated as a potential new technology for radiation hard optical links in high-energy physics experiments (HEP). We went through the entire process of chip design, from electro-optical device simulations to mask layout and submission. The mask layout comprises various active and passive test structures. Some of those test structures are custom- and pre-designed optical transmitters (Mach-Zehnder modulators) with varied design parameters. These test structures will be used to assess how varied design parameters affect the radiation hardness of such devices. The chips are currently being fabricated at imec and CEA-Leti. Irradiation test results will be produced as soon as the chips are ready (10/2015 for imec and Q1/2016 for CEA-Leti). To our knowledge, this is the first submission of custom designed photonic chips in the HEP community.

References

[1] S. Seif El Nasr-Storey et al., IEEE Transactions on Nuclear Science, vol. 62, no. 1, pp. 329-335, 2015
[2] R. Soref and B. Bennett, IEEE Journal of Quantum Electronics, vol. 23, no. 1, pp. 123-129, Jan. 1987

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For additional information:
marcel.zeiler@cern.ch