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***Short-Abstract*—An heteroepitaxial bonded III-V on Si nanopatterned waveguide is demonstrating a wavelength selective behavior thanks to a super-periodicity added to its sub-wavelength, below band-gap, structuration. Effective Medium Theory has been implemented for modal effective index determination, allowing a quick and nevertheless detailed investigation of the role of a large number of geometrical parameters. Such nanostructured waveguides offer the versatility for designing complex geometries required for hybrid advanced optical functions on silicon.**

I. INTRODUCTION

The future of all optical networks links relies upon hybrid silicon photonics. III-V materials are still required for optical functions that silicon is not able to efficiently produce. We have developed oxide-free bonding of III-V InP-based material on nanopatterned silicon waveguides [1]. Including a sub-2D photonic bandgap structuration in the lateral claddings of the silicon waveguides provides a large versatility for tailoring the propagated optical mode, thus enabling advanced hybrid optical functions. We demonstrate here that adding further to this 2D structuration a super-periodicity in the propagation direction provides wavelength selectivity. Such a design could be implemented for example within monomode hybrid laser, allowing a large versatility for the mode shaping and selected wavelength.

For modal simulation, being in the sub-photonic band gap regime Effective Medium Theory –EMT–allows determining the modal effective index. EMT is of interest when modal behavior of optical waveguides including nanopatterns is calculated since simulation of the exact geometry requires a tiny meshing which leads to highly demanding computational resources. EMT then offers the advantage of calculating large structures including tiny geometries, which otherwise have to be limited in size due to computational overflow on standard equipments. A parametric study is also possible for device performances optimization. We have here implemented EMT for fast and accurate modal calculation, thus investigating a large variation range for the several geometrical parameters contributing to the mode effective index.

II. DESIGN OF THE PHOTONIC CRYSTAL WAVEGUIDE USING EFFECTIVE MEDIUM THEORY

EMT has been demonstrated to fully represent a periodic nanostructured medium when its pitch Λ is much smaller than the wavelength λ, $\alpha = \Lambda/\lambda << 1$ [2-4]. The nanostructured medium behaves like a uniaxial material, with ordinary index n_e and extraordinary index n_o. We consider here a two dimensional Photonic Crystal -2D PC- serving as a lateral cladding for a waveguide, with propagation along the z direction (Fig.1, left). The core of the waveguide is not structured. For the structured material, in the case of electric field along the direction of invariance, the resulting permittivity of the extraordinary index is the mean value of the involved permittivities [2]. As for the ordinary index, it is obtained from the dispersion curve of a 2D PC calculated by a plane wave expansion method [5]. Both ordinary and extraordinary indices are plotted in Fig.1 right, versus the air filling factor, evidencing the uniaxial behaviour of the patterned material.

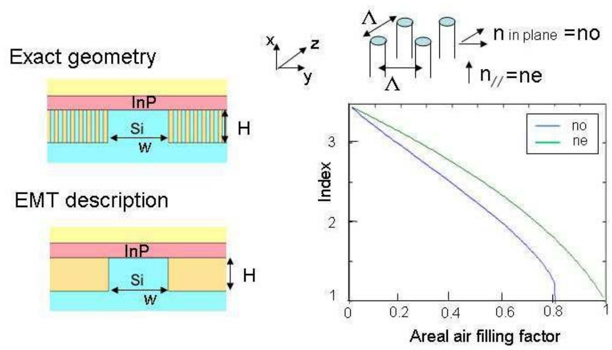

Figure 1: Left: schematic of the effective medium operating as the waveguide cladding Right : Extraordinary index and ordinary index versus areal air-filling factor

We use the commercial COMSOL RF mode solver module. We calculated the eigenmodes of a hybrid waveguide in the case of a 400nm-thick InP layer bonded on a 550nm-thick Si guiding layer, on SOI, and including 2D periodic nanostructured claddings on both sides. Calculated modes are generally classified as quasi-TE and quasi-TM, unless hybridization is too strong. A parametric study is performed according to the PC waveguide width *w*, varying the trench depth *H* and air-filling factor *f* (Fig.1, left). Holes parameters (*H, f*) are determined in order to provide large higher order mode selectivity, in TE polarization, according to the waveguide width *w*. When the effective index of the fundamental TE mode is obtained, the added super-periodicity is calculated to provide wavelength selectivity for 1.55µm. It consists in a single larger hole added each other longitudinal period (Fig.2-b). A 30% increase has been chosen for the larger hole to ensure the required feedback.

III. Fabrication and Measurement of Wavelength-Selective Hybrid Waveguides

The sub-λ 2D photonic bandgap structuration parameters of the fabricated hybrid waveguides are the following: it consists in a square lattice of holes, diameter 60nm, period in the 150 nm range and *f* = 12.5%. The layers are a 400nm-thick InP layer, oxide-free bonded on a 550nm-thick Si guiding layer [1]. For a waveguide width *w*=0.6-µm, the optimal hole depth for a large higher order modes rejection in TE polarization is *H*=380nm.

Fig.2-a is a SEM image of a cleaved facet of a fabricated hybrid waveguide. Two cleaved facets waveguides including 20 rows of holes on both sides, have been measured on an end-fire set-up including polarization maintaining tunable sources and injection fibre for TE polarization. Collection is performed with a microscope objective allowing simultaneous observation of the guided mode and collection in the fiber. The feedback efficiency of the larger hole added each other longitudinal period has been experimentally investigated through changing its position from the first to second and third row (Fig.2-b).

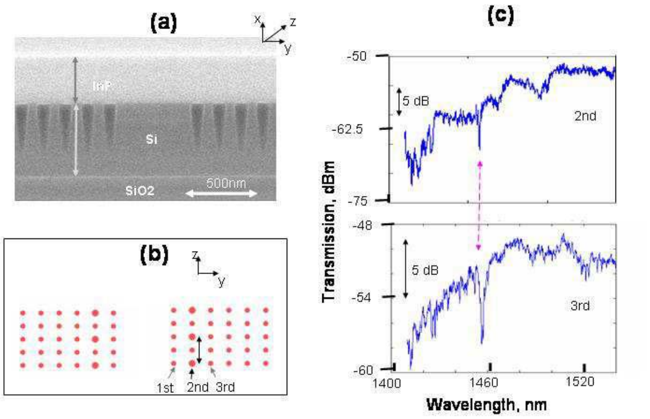

Figure 2: (a): InP membrane bonded on a PC Si waveguide on SOI , SEM view of a cleaved facet (b) : Schematic of the added super-periodicity in the propagation direction when the larger hole is on the 2nd row, (c) Transmission versus wavelength evidencing the signature of the added periodicity in the sub-λ nanostructured Si waveguide.

Fig.2-c shows the transmission versus wavelength, in the case of a waveguide width *w*=0.6µm, for a 30% larger hole. The sharp dip visible at 1455nm corresponds to the feedback effect of the additional periodicity. Its spectral position is in reasonable agreement with the effective index mode calculated with EMT. When going from a larger hole on the 2nd to the 3rd row (Fig.2-c top to bottom), the feedback wavelength is not affected since the periodicity is the same. Concerning the feedback efficiency, both transmissions demonstrate a ~7dB dip. This is related to the weak lateral effective index step. The tail of the optical mode is decaying relatively slowly, thus the feedback strength does not change much between 2nd to 3rd row. As regarding the overall transmission, we attribute the relatively large variation in overall transmission to the cleaved facets quality. Further characterization is under progress to sort the role of all the involved parameters.

Such a wavelength-selective hybrid waveguide is a good candidate for hybrid single mode laser design.

IV. Conclusion

We have proposed and experimentally demonstrated the wavelength-selective operation of a sub-photonic band gap 2D photonic crystal hybrid waveguide, when a super-periodicity in the propagation direction has been added to the effective-medium. Effective Medium Theory has been proven to be a reliable tool for modal effective index determination, allowing designing complex geometries required for advanced optical functions.

Such an effective medium design offers a large potential for the conception of any kind of hybrid waveguide dedicated to advanced optical functions, since a tailored geometry can be easily inserted. The great advantage is that changing the geometry in order to obtain a new optical function does not require developing a new technology for material bonding.

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