Optical radiative cross-talk in photonic integrated circuits

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The mitigation of cross-talk effects between photonic devices integrated onto the same chip is of primary importance in order to respond to the pressing demand of high component density and circuit area reduction. In this work, we present an extensive experimental investigation on the radiative optical cross-talk in InP integrated circuits. Results demonstrate that waveguide sidewall roughness generates an interference signal between passive devices that decreases quadratically with the distance. The phase coherence between exciting and coupled modes is investigated as well, revealing a gradual decorrelation for increasing gap between the waveguides.

Introduction

In the last decades integrated photonics observed an increasing demand of circuit complexity with a trend that is destined to continue in the near future [1]. Larger scale of integration implies device footprint reduction and more relevant issues related to cross-talk interaction. Investigation and characterization of these phenomena is then of primary importance for a proper development and design of highly integrated photonic circuits.
A significant fraction of the waveguide propagation loss is generated by imperfections of the guiding structure, and in particular by sidewall roughness [2]. Radiation mode excited in one waveguide can partially reach another device placed nearby and be coupled back to a guided mode of the second structure, thereby acting as an optical cross-talk vehicle. Models and experimental investigation have been proposed in literature for radiation mediated coupling in both waveguides [3] and integrated components as directional couplers [4]. However, to the best of our knowledge, information is still missing on the dependence of optical cross-talk power on the waveguides distance as well as on the phase properties of the coupled light.
In this work an experimental investigation of the radiative cross-talk between adjacent passive waveguides is presented. The dependence of the coupled power on the distance between the waveguides is studied and compared to the results obtained with electromagnetic simulations to confirm the absence of any effect related to the evanescent field. The phase correlation characteristics of the coupled modes is investigated as well.

Cross-talk power dependence on the waveguide gap

Experimental analyses were carried out on the test structure of Fig. 1, which was realized with the weakly-etched InP-based rib waveguide described in [5] and reported in the inset of the figure, with a width of 2 μm. This waveguide is particularly adapted for this analysis, because the lateral slab provides a vertical confinement to radiation modes, emphasizing cross-talk effects between neighbour structures. The device is composed by two waveguides. The first one ("direct waveguide", beginning at port A) is a s-bend with three straight sections and two bent waveguides and a very smooth aspect ratio of 6 mm $\times$ 100 μm. The second waveguide ("coupled waveguide") begins few hundreds of microns after the beginning of the long central straight section of the first one to avoid coupling due to field radiated at the first bend. The distance between the two waveguide varies on different devices from g = 2 μm to g =30 μm while the straight coupling section is kept fixed at 3 mm. The distance between the output ports (ports B and C) is 30 μm for all the devices. The shape of the device reduces the straight-light coupling between the input fibre (at port A) and the coupled waveguide.

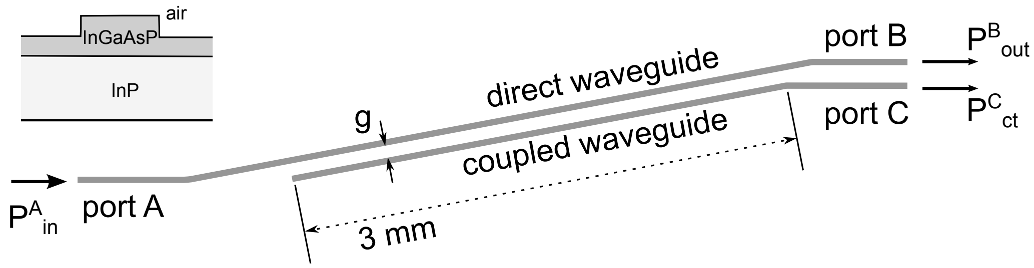

Figure 1: Test structure designed for the cross-talk characterization. The waveguide structure is reported in the inset.

In the experimental characterization, the input light is coupled at port A and the output power at ports B and C is measured, for different gap distances, by an Optical Spectrum Analyser. The measurements of P^B_{out} and P^C_{ct} are shown in Fig. 2 for the TE mode when P^A_{in} = 0 dBm. Similar results were obtained for TM state of polarization. Blue marks represents P^B_{out}, namely the power that remains in the direct waveguide. The power level is substantially constant around -12 dBm at any gaps, indicating that the light coupled in the other waveguide is a small fraction of the total. Since the coupled power P^C_{ct} (red circles) falls from a values of about -15 dBm at g =2 μm to less than -50 dBm at g =30μm, the ratio between P^B_{out} and P^C_{ct} drops from 0 dB to -35 dB. The experimental data suggests a dependence on the gap in the form g^{-x} with $1 < x < 2$ (red dashed line, for $x = 2$) if the point at g = 2 μm (where evanescent coupling is dominant) is excluded from the fitting.
To correctly interpret these results, the pure evanescent coupling contribution to the total coupled power was simulated. Evanescent coupling (blue and black lines in Fig. 2 for port B and C, respectively) is the dominant mechanism for g < 2 μm, where a strong power exchange oscillation between the two waveguide can be observed. For g = 3 μm and g = 5 μm the device works in an intermediate situation, where there is a residual contribution of the evanescent coupling but the radiative cross-talk becomes a significant fraction of the total power exchange. This can be argued from the difference between the predicted power at port C from pure evanescent coupling and the higher power actually measured. Finally for $g \geq 10$ μm only the coupling via radiative modes exists.
The major limit to the dynamic range of the measurement is represented by the presence of light in the thin slab region around the rib waveguide structure. This feature can be seen in Fig. 2 where the gray marks represent the power measured moving the output fibre by about 100 μm far from port B (P_{sub}). Reasonably, this power does not depend on the value of the gap since is related directly to the input fibre excitation. It is clear how

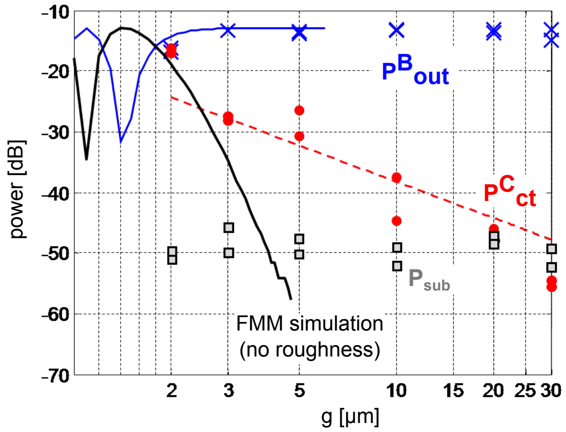

Figure 2: Output power at the direct (P^B_{out}, blue mark) and coupled (P^C_{ct}, red marks) waveguides and in the slab/substrate region (gray dots) as function of the gap. Simulation of the evanescent coupling regime are superposed for comparison (blue and black solid lines).

the power level in the slab results to be a real limit to the measurements of the cross-talk efficiency, that between 20 μm and 30 μm can be hardly distinguished from this noise floor.

Phase decorrelation of coupled modes

In order to characterize the properties of the phase of the mode excited by radiated power, the test structures used in the previous section have been reversed in order to injected light at port C. In this way it is possible to exploit the two strong reflection generated by the abrupt termination of both waveguides (in the middle of the chip and at chip facet) as phase measurement points. The experiment was conducted with an Optical Frequency Domain Reflectometry (OFDR) technique [6], which allows an interferometric analysis of the light reflected along a waveguide. An example of the measured space-domain trace is reported in Fig. 3 (a), which represents the reflected power as function of the optical distance with respect to the input facet. The first highlighted peak refers to the reflection generated by the termination of the input waveguide. The second is due to the light that crosses the coupler, is reflected by the chip facet and crosses the coupling region a second time, reaching again port C.

The phase spectra of this reflections can be measured and the relative difference computed at each wavelength. Figure 3(b) represents this quantity, compensated for the phase contribution related to propagation, for the devices with g = 2,5,10 μm. In Fig. 3(c) the probability density functions (PDFs) of the previous data are reported. In the evanescent coupling regime (black solid line) this difference is substantially zero for the entire considered bandwidth, consistently with this type coupling which is coherent and preserve the phase relation between exciting and coupled mode. The PDF is a narrow peak around zero (black squares), confirming that the phase difference is almost zero at each wavelength. For g =5 μm (blue solid line) some noise appears in the spectral data and the PDF radically changes its shape, spreading around zero (blue squares), and indicating that the light is affected by radiation mode coupling. This is confirmed by the device with g = 10 μm (red solid curve) where the coupling is due exclusively to radiative modes and strong spectral oscillations appears and the PDF.

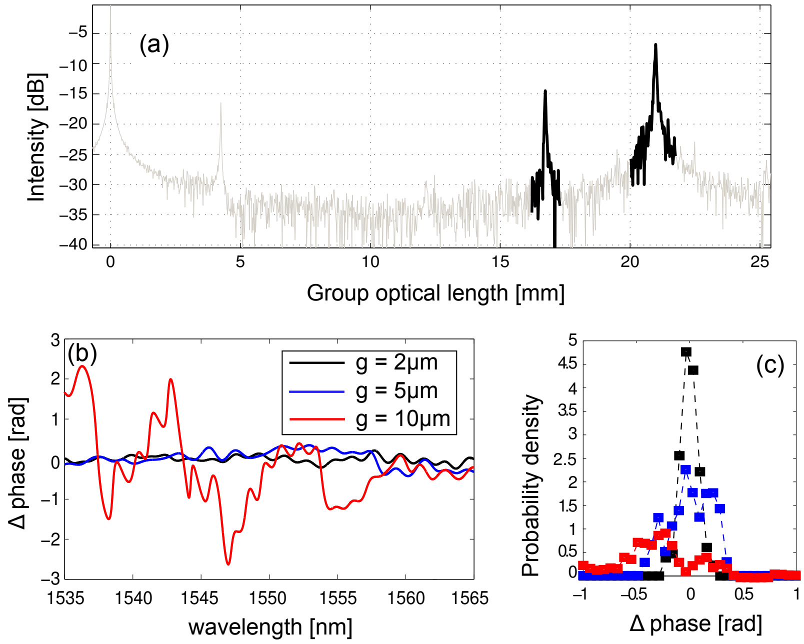

Figure 3: (a) Example of space-domain trace measured for the reversed devices (light input form port C). Two strong reflections are recognisable. (b) Spectra of the phase difference between the reference and the coupled signal for different gaps and (c) corresponding PDF.

We can then conclude that the coupling mediated by radiative modes (unlike evanescent coupling) is an incoherent mechanism, which does not preserve the phase relation between the coupled modes in the adjacent waveguides and hence causes a decorrelation of the coupled power from the modes of the original waveguides that excite the radiation modes. This decorrelation becomes stronger when the waveguide distance increases.

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