Scattering-related crosstalk in photonic waveguides

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Abstract: A comprehensive analysis of the crosstalk between integrated photonic waveguides generated by roughness-related scattering is presented. A power-law dependence on the waveguide distance is demonstrated, confirmed also by simulations performed with a specifically developed model based on the volume current method.

In the near feature, integrated optics will face a challenging request for larger scale of integration, with the necessity to increase the number of components per unit area of the chips. Crosstalk phenomena will hence become a real limiting factor, eventually compromising the functionality of densely integrated circuits[1]. In particular for high-index-contrast technologies, a source of crosstalk can be represented by the power leakage generated by sidewall roughness[2]. Part of the scattered light can reach a nearby waveguide, causing an unwanted optical power exchange between ideally uncoupled waveguides[3]. In this work we present an experimental characterization of the properties of roughness-induced optical crosstalk in photonic waveguides, demonstrating the emergence of a radiative regime able to support a coupling also beyond the effects of evanescent coupling. The exploited test structure is represented in Fig. 1(a). The device is formed by a S-shaped waveguide comprised between ports A and B (direct waveguide) with a second 3-mm-long straight waveguide (adjacent waveguide) running parallel at a gap distance *g* and defining the coupling section. Gaps between 2 μm and 30 μm have been considered. The aspect ratio between input port A and output port B is 6 mm × 100 μm and the shape of the device was designed in order to reduce the impact of stray-light generated by the input fibre (port A) on the measured power at ports B and C. Two different waveguides has been considered for the fabrication of the device. The first one, represented in Fig. 1(b), is a shallow etched InP-based rib waveguide with a 1-μm-thick InGaAsP core and an etch depth of 600 nm. The second waveguide is a deeply-etched version of the same cross-section (Fig. 1(c)), with an etch depth of 1.7 μm. In both cases the waveguides are 2 μm wide.

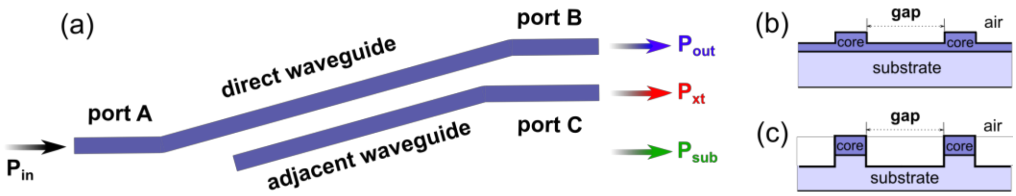

Fig. 1: (a) Design of the test structure exploited for the experimental characterization of the radiative optical crosstalk. Two different cross-sections have been used for the devices: (b) shallow and (c) deeply etched InP-based waveguides.

For all the fabricated structures, the crosstalk was measured coupling light at port A (P_{in}) and measuring the average power at port B (P_{out}) and C (P_{xt}) as function of the gap *g*. The normalized power $P_{xt}/(P_{xt}+P_{out})$ represents the crosstalk from the direct to the adjacent waveguide. Results for TE polarized light are reported in Fig. 2(a) and 2(b) for the shallow and deeply etched waveguide cross-sections, respectively. In both cases the dynamic range of the measurement is limited by the presence of substrate modes excited by the input fibre and propagating throughout the chip. The power P_{sub} (green squares) carried by these modes was measured laterally shifting the output fibre 50 μm far from port C. For the shallow etched waveguide, the crosstalk is as high as -3dB at g = 2 μm and drops to less than -40 dB at g = 30μm. In order to evaluate the contribution of the pure evanescent coupling to the power transfer between the waveguides, the test structure was simulated with a commercial electromagnetic simulator based on the Film Mode Matching (FMM) method[4] for perfectly smooth sidewalls. Simulation results are shown in Fig. 2(a) with blue and black lines for ports B and C, respectively, and allow to identify different coupling regimes. Evanescent coupling well explains the

-3 dB crosstalk measured at g = 2 μm while, for larger gaps, the measured power coupling largely exceeds the results of the simulations, suggesting the presence of a contribution arising from the roughness-related scattering. For g = 3 μm the device works in an intermediate regime, where the measurements show a power coupling 5 dB higher than the simulated evanescent coupling. For $g \geq$ 5μm only radiative coupling mechanism occurs. Radiative coupling decreases versus distance g with a much slower scaling law than the exponentially decaying evanescent coupling, exhibiting a power-law dependence g^{-x} on the gap distance, with $x \approx 2.8$ for the structure under consideration. To support this result, we developed a model to evaluate the expected radiative crosstalk between two parallel waveguides. The model is based on volume current method[5], where roughness on both waveguides is modeled as an array of dipoles. In the direct waveguide the array is excited by the propagating guided mode, generating a radiation field that is collected by the dipoles of the adjacent waveguide. This second dipole array produces itself a scattered field exciting a guided mode in the adjacent waveguide. The results obtained through this model (red dashed line in Fig. 2(a)) well match experimental data, thus confirming the g^{-x} scaling law of the radiative crosstalk versus gap distance (with $x \approx 2.8$). For the deeply-etched waveguides of Fig. 2(b), optical crosstalk effects are reduced of more than 15 dB compared to shallow etched waveguides. P_{xt} is as low as -25 dB at g = 2 μm and it drops below the substrate power level (about -35 dB) for a gap distance g > 2 μm. Interestingly, the substrate power level is the same in both cases. Because of the tight confinement of the optical mode in the waveguide, the contribution due to pure evanescent coupling (black line) can be neglected in all the measured structures, so that the weak power transfer between the two waveguides is entirely related to radiation effects. Also in this case the g^{-x} scaling law ($x \approx 2.8$) holds well, at least for $g \leq 3$ μm. Beyond this limit, substrate modes become predominant, with a contribution P_{sub} independent on the gap distance.

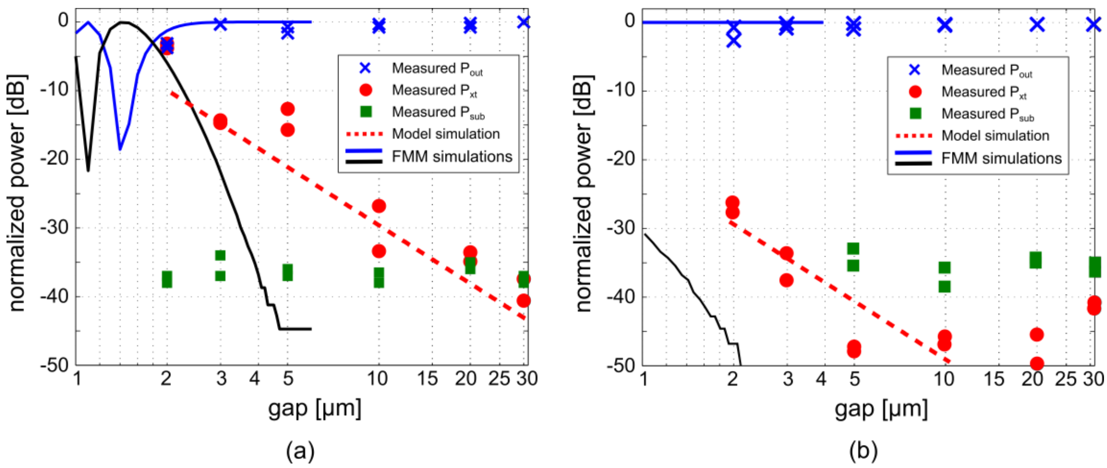

Fig. 2: Power crosstalk as function of the gap between parallel waveguides for (a)shallow and (b) deeply etched waveguides. Both P_{out} (blue crosses) and P_{xt} (red dots) have been measured and compared with FMM simulations of the evanescent power coupling (blue and black solid lines). In both cases, the presence of substrate modes (green squares) limits the dynamic range of the measurement. For shallow etched waveguides, radiative crosstalk shows a power-law dependence on the waveguide distance, confirmed also by the simulations performed with the developed model (red dashed line).

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