Broad Periodic Waveguides: Slow Light and its Reconciliation with Cavity Modes

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ABSTRACT

A "slow" high-order mode in a photonic crystal waveguides can be exploited using conversion from a "fast" fundamental mode to achieve demultiplexing. A further interesting slow-light regime of more general broad periodically corrugated waveguides with many modes will be shown: it arises from higher-order modes coupled among themselves and hinges on the familiar Littrow diffraction geometry. We will show some of its less obvious features, notably the "critical coupling" regime for maximal slow down. This "critical coupling" regime induces modes whose transmission closely follows that of multiple Fabry-Perot resonators. Experiments on broad Silicon-on-Insulator waveguides evidencing this regime are shown. We argue that this system reconciles *cavity* vs. *band-edge* enhancement and is dual to the popular "CROW" introduced by Yariv in 1999.

Keywords: Broad waveguides, slow-light, cavity confinement, multiple Fabry-Perot, Littrow diffraction.

1. INTRODUCTION

Recently, *slow light* has often been embodied through photonic crystal waveguides of nearly one missing row (W1), essentially monomode waveguides [1, 2]. It is however possible to have slow light in much broader waveguides. The coupling of different modes in broader waveguides (e.g. W3 or W5) can lead to functions such as demultiplexing [3-5]. The success of coupled mode theory in these systems pushed us toward investigating even broader waveguides. In waveguides such as W15, we evidenced "Littrow lasing" [6]. This led us on the one hand to investigate spontaneous emission in such broad guides[7-9].

It also led us to consider multimode coupling *per se* and to evidence the regime of critical coupling [8, 10-12] (see also ICTON 2010[13]) detailed below. A specific consequence was the ability to put up a recipe for slow light [14]. In this paper, we discuss broad corrugated waveguides nearly reaching the "critical regime". We discuss realistic finite-difference time-domain (FDTD) simulation and first results on SoI waveguides made at EpixFab (Ghent). They notably allow us to show that the behaviour of broad guides of adequate length is comparable to that of multiple Fabry-Perot systems.

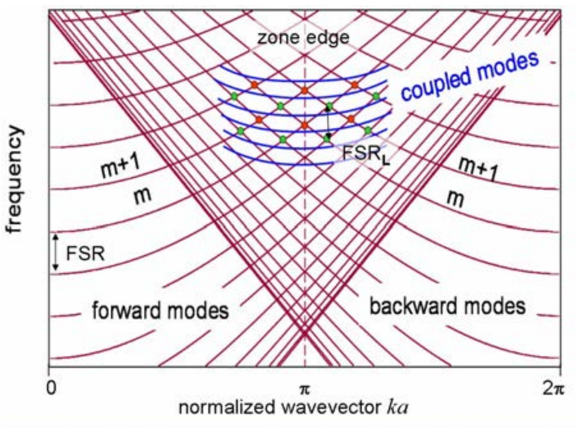

Figure 1. Crossing of forward and backward modes in an ideal broad waveguide without corrugation (half-hyperbola) form a nearly regular mesh (dots). The corrugation can couple these modes and form hyperbola of "slow modes" centered at the band edge $ka=\pi$.

On Fig. 1, we show the well-known hyperbolic-shaped modal dispersion for a broad waveguide, labelled m, m+1, … and separated by the FSR (at $k=0$). We also show the corresponding backward modes, shifted by $G_1 = 2\pi / a$. The crossing of both kinds of modes forms a locally regular mesh that we have underlined by dots in the central zone edge region. Note the local separation of equivalent dots, $FSR_L < FSR$. The periodic corrugation has the effect of coupling both sets of modes[12], in a way reminiscent of studies made for Landau-Zener manipulation of Rydberg atoms in the 90's [15], an analytical description that we are currently investigating.

The coupling of both set of modes can be made in variable amount. For a specific coupling strength given by the relationship $\kappa_{m,m'} = FSR_L / \pi$, [8, 11, 12], the coupled modes dispersion flattens out at the zone edge, being equally pushed downward by higher modes and pushed upward by lower modes. This is the critically coupled regime (CCR). Some wiggles remain in the resulting dispersion, but slow-down by a group index ratio of $n_g ' / n_g \sim 10 - 30$ can be realised in a sizable window of a few modes. We have further investigated this CCR in simulation and in a silicon-on-insulator (SoI) system.

2. SIMULATION RESULTS FOR A LONG DEVICE

We had already made a design of a resonator based on these slowed-down modes [11]. However it was for one polarization which does not apply to the silicon-on-insulator (SoI) examples discussed below, where the field is coupled by a 1D grating and is called TE in the access guide, i.e. the field points "inside" the thin silicon slab of interest instead of "outside" the slab. We found generally similar results in this polarization which was also designed for 45° Littrow operation (effective index ~2.8 in SoI, period ~385 nm for wavelength ~1550 nm). A main difference was that for a triangular corrugation on one side as in [11], the critically coupled regime (CCR) is attained around a height/period *h/a* ratio much higher than 1.25 [11]. It is rather attained around a ratio of 3.0, or less, *h/a*~2.5, for a slightly modified shape departing from triangular due to customary lithographic biases.

We were interested, however, by first pushing the simulation further in terms of device length. The result is shown in Fig.2 in the form of a map of transmission as a function of frequency (abscissa) and depth (ordinate). The device modelled is sketched on the right. Its length is called "T6" and allows twice a resonant round-trip. It has order $m = 50$. The order m relates to the width w of the waveguide according to $m\lambda = 4\cos(\pi/4)\, w\, n_{\text{eff}}$.

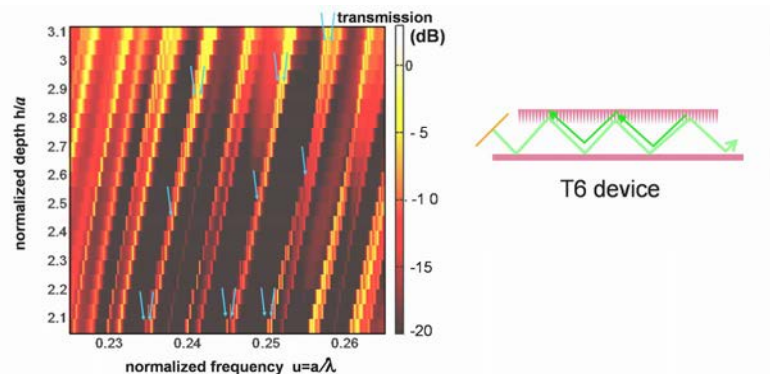

Figure 2. Colour map of transmission in dB of a T6 device(shown on right) vs. normalized frequency and normalized height for a nearly triangular tooth shape. The CCR is the dark central region. The doublets on the edges of the CCR are pointed by bluish arrows. They tend to evolve in singlet at the exact CCR.

As can be seen on the figure the coupled modes form narrow transmission windows in the CCR region, the area with a black background. Instead of the isolated peaks that we found in shorter devices, we now find that most of the curves are transmission doublets (bluish arrows), associated with the symmetric and antisymmetric combination of the two resonances sketched above. Looking in more detail, the dominant feature is a doublet, but of variable relative strength. The most asymmetric case arises at CCR, where in many cases the result can be assimilated to a singlet transmission. We thus see that there is an intrinsic difficulty to excite both modes when ideally resonant, a trend that is not yet discussed much to our knowledge in such a multimode case.

3. EXPERIMENTAL RESULTS

The technique to obtain the results has been described elsewhere. The sketch of the setup used to measure the EpixFab samples with their access guides is given in Fig. 3 below. Details will be reported elsewhere. Devices of variable length and variable *h/a* ratio were used to track for the CCR and to understand the effect of guide length.

Fig. 4 describes a typical experimental result for a T6 waveguide, here for order $m = 75$ (see above for definition), hence a free-spectral range $FSR_L / 2$ of $\Delta\lambda = \lambda / m \approx 20$ nm. Data are measured between 1520 nm and 1584 nm with typically a 200 pm step. In normalized units, we work around $u = a/\lambda \sim 0.25$, hence a spacing $\Delta u \sim u/m \approx 0.0033$ without dispersive effects.

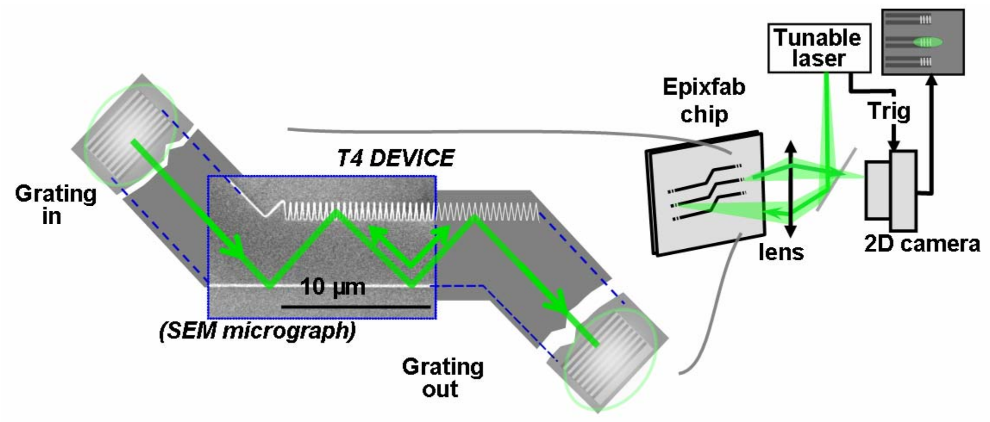

Figure 3. Sketch of a typical EpixFab chip/sample and of optical setup to measure it with a tunable laser triggering the camera.

We know from a study of the full set of samples that the CCR takes place at nearly *h/a* = 2.50, which corresponds to a modest deviation of the shape from a perfect triangle toward a "bottle shaped" tooth with eroded apex. The two spectra shown here are chosen reasonably above CCR (*h/a* = 3.0, top) and more exactly at CCR (*h/a* = 2.50, bottom).

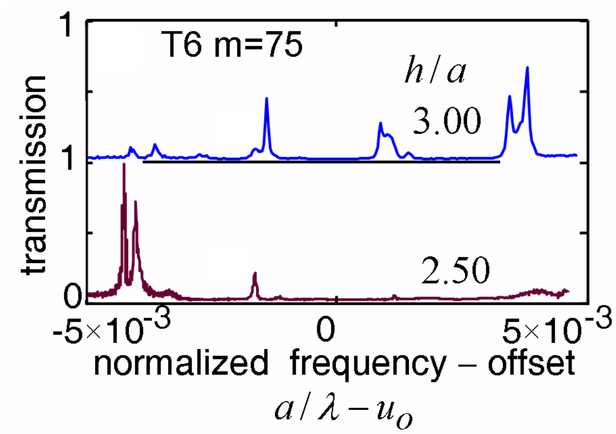

Figure 4. Experimental spectra for waveguides of order m = 75, of length "T6" (see Fig.2) and of height/period ratio h/a = 3.00 and 2.50 as indicated. Note the doublets for h/a = 3.00 which become more markedly singlet-type for the more exact CCR condition h/a = 2.50.

While the spectrum at *h/a* = 3.0 still shows reasonably well defined doublets at all resonances, the one at *h/a* = 2.50 show rather singlets at the two most resonant positions where they can be guessed. The leftmost peak is still a doublet, but a full comparison with the simulation data is underway to understand the different results, and their physical significance.

4. DISCUSSION AND CONCLUSION

We first note that the transmission level is acceptably constant and relatively high in both samples shown, even though we approach the CCR. Normalization is made with a straight guide, hence transmissions of $T > 0.2$ in the center of the spectrum (where intensity is large enough to grant minimal errors) is quite acceptable.

The other feature that we note is the good agreement of doublet / singlet behaviour between theory and experiment. This kind of frustration of the doublet transmission could be related to the difficulty of coupling to any kind of slow modes, which may depend for instance on the role of evanescent modes as noted recently [16].

Another interesting point is to see that we have an open resonator with relatively high quality factors (Q ~ 10000 or above), good for nonlinear optics purposes. It is also an interesting system if regarded as a waveguide because it pushes the "photonic conductance theorems" such as the work in [17] to its limits, since we have hardly any conductance (in our excitation directional geometry), but we have regular photonic bands.

This leads us to the last point of our discussion: we have a device that behaves exactly like a set of two Fabry-Perot systems (except close to exact CCR), while it is also a single waveguide with perfectly regular wavelength-scale periodicity, and no defect at all within this periodicity. The peculiarities are thus stemming from the conditions of excitation and the physics of the slow-light modes obtained at the CCR condition.

We therefore argue that this structure is dual to the popular "CROW"[18] slow-light concept, whereby coupled cavities allow for a slow propagating photon. In our case, we just have the *converse concept*, whereby equivalent *cavities emerge from an otherwise "uniform" waveguide* (only a wavelength-scale periodicity). We thus reconcile two pillars of photonics, namely cavity confinement and slow-light confinement: by exhibiting a waveguide that can be fundamentally described by slow light confinement in flat photonic bands, but that nevertheless realizes a cavity-like confinement.

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