Broad periodic waveguides with critically coupled modes for open resonator operation

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Abstract-**The coupling of higher-order modes of broad periodic waveguides emerges when using photonic crystal waveguides. The specific idea of critically coupling such modes to generalize slow light and flat bands is examined for its various merits, notably to form open resonators. The coupled-mode-theory (CMT) also provides a simple description of spontaneous emission in them.**

I. INTRODUCTION

Photonic crystal (PhC) have paved the way for less orthodox uses of waveguides (WG) , and notably of higher-order modes in broad waveguides. When both the fundamental mode and a high-order mode are confined in a PhC-WG, their coupling arises only when wavevector and frequencies both coincide, which means a narrow window of coupling, the so-called Mini StopBand.

This has been used to provide demultiplexing action based on PhCWG, with the possibility to extract on the side of a guide a series of specific wavelength at arbitrary locations, unlike the classical spectrometer approaches.

The last progresses in this area were made on SoI wafers made with EpixFab (Ghent)[1]. Their design and modeling form a first case of an open resonator. We notably reinforced the crosstalk up to ~15 dB by adding a filtering waveguide cloning the first one in all respects but the modal coupling which was cancelled by appropriate boundaries.

In the following we examine the distinct case of coupling among higher modes only. This brings a bunch of concepts, mixing Littrow diffraction, slow light and open resonator behavior, and therefore warrants some detailed description

II. BROAD PERIODIC WAVEGUIDES, CRITICAL COUPLING, AND EQUIVALENT CAVITIES

The basic idea is to simply consider a bunch of higher-order forward modes in a broad waveguide, and to wonder what happens around the Brillouin zone boundary, when this bunch of modes is coupled to its backward counterpart due to a periodic pattern. Such a WG need not be a PhC-based one.

Such a pattern may lie in a distributed way across the guide core, or may lie only at the side.

Figure 1 illustrates how the modes are transformed (coupled mode theory, CMT). Gaps open at every crossing, but as discussed recently[2], if the coupling has an adequate strength, the so-called critical coupling regime (CCR) optimally flat bands are formed at the Brillouin zone edge [3, 4]. In some more details, the set of coupled modes has a locally hyperbolic behavior [4], with wiggles reminiscent of the initial modes superimposed on it. The gaps of each crossing coalesce along these hyperbola into "stripes of minigaps" [5].

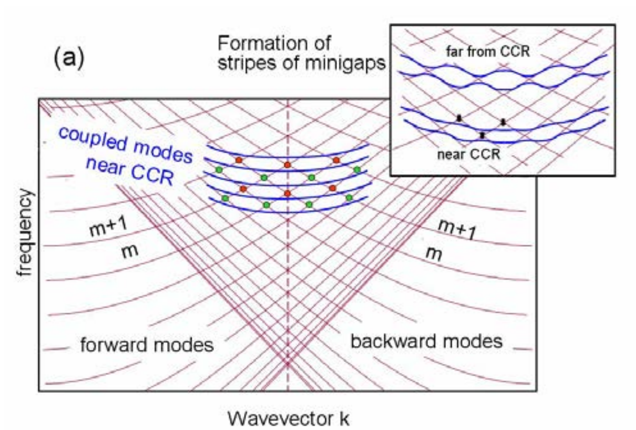

Figure 1. Modes of a broad waveguide (thin lines), submitted to folding due to periodicity at k=π/a (dashed line). The coupled modes form hyperbola. The wiggles are minimized at the critical coupling regime (CCR).

This critical coupling correspond in practice to a strong backward feedback in the waveguide, which correspond in turn to Littrow back diffraction [6, 7].

Our initial idea to implement this system was to use a single-material system such as bulk silica (Fig.2) [8] used at 45°, and further in "TM" configuration (Electric field E normal to the figure).

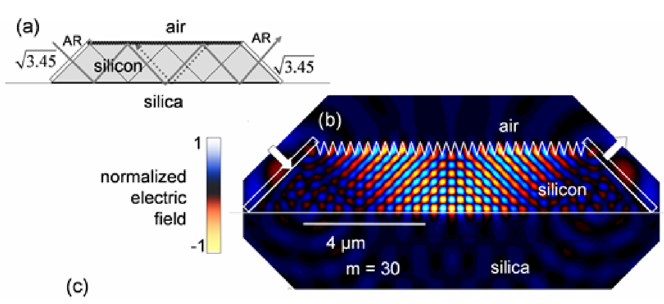

Figure 2. (a) basic design of open resonator broad waveguide by ray tracing; (b) example of a stationary mode calculated by PhotonDesign 2D FDTD, there are two anti-reflection coatings on the 45° facets.

By modeling the transmission of this system, evenly separated peaks appear. As can be guessed from Fig.2, the system tends to behave as a Fabry-Perot, but the grating in reflection play the role of the mirrors in transmission.

We are currently looking at a SoI version of this system using the "TE" configuration, i.e. the field normal to the figure being magnetic and not electric.

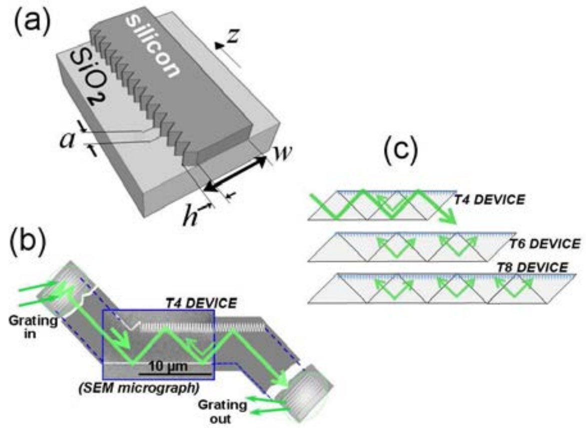

Figure 3. (a) SoI broad periodic waveguide; (b) practical use with vertical coupling; (c) Ray-tracing and decomposition in tiled triangles. Increase of length is equivalent to multiple Fabry-Perot behavior.

We thus have a wavelength-scale periodic system that can behave as a cavity. Insofar as cavity confinement and band edge confinement are opposed, the usual example of the combination idea is the "CROW" (Coupled Resonator Optical Waveguide). Our broad periodic waveguides offer the reciprocal concept, that is, a perfect waveguide with small-scale periodicity but without the slightest defect, which nevertheless behaves as a set of cavities.

We have reported first results at a recent conference [9] and we will attempt to give more clues.

III. Spontaneous Emission

Spontaneous Emission in a complex structure depends on the local density of states (LDOS). Considering our problems as two-dimensional ones, it is true that determining the exact LDOS is a demanding work. But in many cases, the lateral location is not so important, and an average, or a single value, can factorize. A still generic issue remains the emission from a nearly 1D system, but with strong interferences inside. Critical coupling can be thought as a coupling among the strongest ones : it relies on efficient Littrow diffraction, similar to the blaze effect in gratings.

We have recently discussed the capability of 1D CMT in multimode case, to predict the main aspects of a spectrum when a source is moderately distributed inside WGs.

A typical pattern of emission spectrum strongly modulated by stripes of minigaps [10] is shown below.

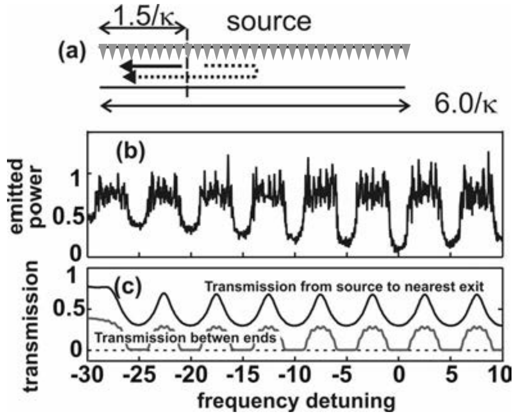

Figure 4. (a) Source in broad periodic waveguide at a specific distance from exits (κ is the coupling constant); (b) spontaneous emission spectrum; (d) various transmission spectra for comparison (no sharp edges on transmission).

We will discuss potential applications of such emitting situations for situation with modulated spectra.

To conclude, the modeling of broad periodic waveguides notably near the critical coupling regim explored here has to combine a few brute force calculations with several conceptual tools.

Acknowledgment

The author thank O. Khayam and EpixFab (P. Dumon, Ghent) for the SoI samples.

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