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# Critical coupling in Cavity Resonator Integrated Grating Filters (CRIGFs) for SHG control

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**Abstract.** We demonstrate experimentally critical coupling for nonlinear conversion in grating-coupled Fabry-Pérot planar microcavities known as Cavity-Resonant Integrated Grating Filters (CRIGFs). Novel asymmetric designs offer Q-factors from 1000 to 7000 and allow critical coupling with maximised SHG. We developed an improved coupled-mode model for the linear and non-linear spectral response of CRIGFs which allows accurate insight on the intrinsic and coupling losses in these microcavities.

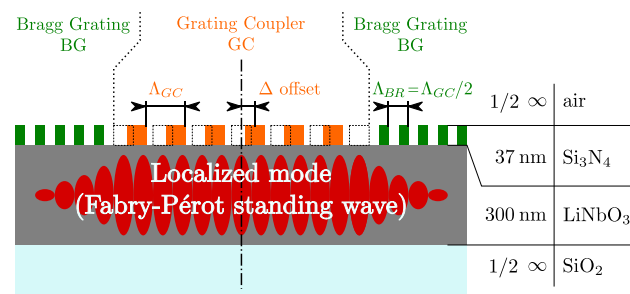
## 1 Introduction

Cavity Resonator Integrated Grating Filters (CRIGFs) are planar Fabry-Pérot microcavities supporting standing-wave localized modes that can easily be coupled from the surface through a grating coupler (GC, see Fig. 1). Contrary to the more common Guided Mode Resonant Filters (GMRFs) that efficiently couple to plane waves, CRIGFs couple to tightly focussed beams matching the extension of the central GC, typically of a few  $\mu\text{m}$ . CRIGFs thus enables denser device integration, but also higher power density which allows studying non-linear processes using low power continuous wave lasers.

## 2 Non-linear asymmetric CRIGFs

When fabricated on Lithium Niobate On Insulator (LNOI) substrate, the localized mode in CRIGF can provide enhanced second harmonic generation (SHG) [1]. Both spatial and spectral properties of this SHG can be controlled and tuned by engineering the CRIGF cavity. This allow to integrate monolithically in one substrate several SHG microcavities with varying properties that can be addressed from the surface.

Recently, CRIGF with asymmetrical GC were proposed theoretically to fine control the coupling strength of the localized mode to the outside world and achieve exalted Q-factors [2]. This approach ensures coupling losses tuning while keeping other resonator properties (resonant wavelength, mode extension, etc...) constant and thus enables reaching critical coupling.



**Figure 1.** Schematic of the CRIGF : planar Fabry-Pérot cavity (green bragg gratings) supporting a localized mode coupled by an asymmetric grating coupler (orange).

## 3 Critical coupling in CRIGFs

We report the modelling, design, fabrication and experimental characterization of asymmetrical CRIGFs with enhanced Q-factors and SHG conversion efficiency.

More specifically, we fabricated several CRIGFs integrated on an LNOI substrate and measured their linear and non-linear spectral responses for various asymmetry offsets  $\Delta$  between the GC and the standing-wave mode localised inside the planar cavity (see Fig. 1). The asymmetry offset  $\Delta$  allows the fine tuning of input- and output-coupling strength of the mode to the outside world. In particular, for  $\Delta = \Lambda_{GC}/4$ , with  $\Lambda_{GC}$  the period of the GC, the GC and localized mode are in quadrature and the coupling strength is null. By varying the offset  $\Delta$  over  $[0 - \Lambda_{GC}/4]$ , one controls both the Q-factor of the microcavity in the  $\sim [1000 - 7000]$  range (see Fig. 2, red curve) but also the SHG enhancement (see Fig. 2, blue curve). Both Q factor and SHG curves are roughly symmetric around  $\Delta = \Lambda_{GC}/4$  (dashed black line), where SHG signal is null as the coupling strength is also null and Q-

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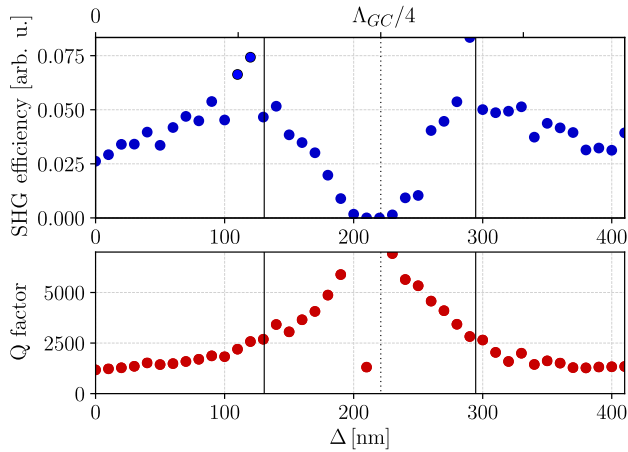
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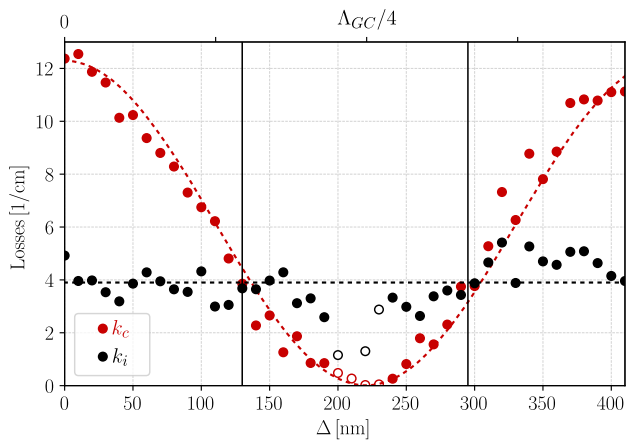
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**Figure 2.** Experimental SHG efficiency (blue) and Q-factor of the localized mode (red).

factor estimation is meaningless (zero signal). On each side of  $\Delta = \Lambda_{GC}/4$ , the SHG conversion efficiency reaches an optimum (solid black lines around  $\Delta = 130$  nm and 295 nm). To ensure that this optimum does correspond to critical coupling, we developed an improved coupled-mode model specifically for CRIGFs, based on the Fano model proposed in [3]. In particular, this model introduces partial coupling between incident focussed beam and the localised mode due to modal overlap mismatch between the incident beam, the GC and the localised mode. Using



**Figure 3.** Estimated intrinsic losses  $k_i$  (black dots) and coupling losses  $k_c$  (red dots) and expected evolution from first principle (dashed lines). White dots corresponds to points where the model is inaccurate (zero signal).

this model to analyse both linear spectral reflectivity and transmission and spectral SHG, we can estimate all the relevant properties of the mode localised inside the CRIGFs. In particular, we can retrieve both the intrinsic losses  $k_i$  and coupling losses  $k_c$  for each fabricated asymmetric CRIGF, as shown in Fig. 3. This confirms that the intrinsic losses  $k_i$  (black dots) stay constant as expected from first principle (dashed black line) while the coupling losses  $k_c$  (red dots) evolve with the asymmetry offset like the integral overlap between the standing wave localised mode and the GC, ie like  $k_{c0} \cos^2(2\pi\Delta/\Lambda_{GC})$  (dashed red line). With these evolutions of  $k_i$  and  $k_c$ , we can confirm that the optimum in SHG efficiency does correspond roughly to  $k_i = k_c$  (black vertical lines), confirming that we achieved critical coupling in CRIGFs. As a an added bonus, this model clearly highlights the fairly high intrinsic losses of our current CRIGFs, opening the way to further design and technological improvements.

## 4 Conclusion

In this contribution, we have experimentally confirmed the theoretically proposed asymmetric CRIGF design for controlled coupling and SHG enhancement. Moreover, we have developed an improved coupled-mode model for CRIGF analysis that give unprecedented insight on the localised mode inside the CRIGF. It will be harnessed to improve both our designs and fabrications steps, in particular to reduce the fairly high intrinsic losses that limit the performance of our current non-linear CRIGFs. In our presentation, we will detail all the design and fabrication steps together with the newly developed model.

## Acknowledgements

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