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ABSTRACT

In this manuscript, we review the recent progress made in nonlinear parametric conversion in grating-coupled Fabry-Pérot planar microcavities known as Cavity-Resonant Integrated Grating Filters (CRIGFs). Having previously established that enhanced second harmonic generation can be obtained in these devices, we discuss the design and experimental demonstrations of technical implementations allowing the achievement of critical coupling and improved conversion efficiencies.

Keywords: Cavity-Resonator Integrated Grating Filter, parametric design, nonlinear conversion, subwavelength gratings, critical coupling, meta-surface

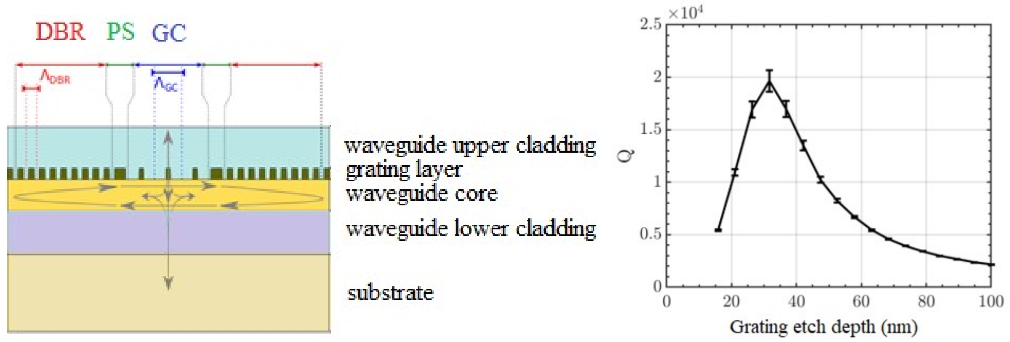
1. INTRODUCTION

Cavity-Resonator Integrated-Grating filters (CRIGFs) are planar waveguide Fabry-Pérot cavities that can be optically addressed by out-of-plane free-space beams thanks to an intra-cavity Grating Coupler (GC) [1], [2]. Their optical response is thus ruled by the resonating modes of the planar waveguide and their GC-mediated in/outcoupling. In particular, upon a judicious selection of the groove depth of the reflecting and coupling gratings, only one cavity mode can be excited by a focussed beam whose spatial extent is of the order of ten wavelengths and lead to a resonant response with quality factors, *Q*, reaching a few thousands [2]. These characteristics mean that these meta-surface devices have typically been used as (de)multiplexing (directional)-waveguide couplers [3], [4], and as tunable filters [5]–[7], the latter enabling, in turn, wavelength-controlled operation of extended-cavity diode lasers [8]–[10]. Besides, when the material used for the planar waveguide core exhibits a high nonlinear susceptibility (such as when it is lithium niobate, $LiNbO_3$), cavity-enhanced nonlinear frequency conversion can readily be achieved as established in [11], [12].

In this paper, we review our recent progress in the design and in the experimental demonstrations of practical technical implementations allowing the achievement of critical coupling and improved nonlinear conversion efficiencies.

2. DESIGN CONSIDERATIONS

As alluded to in the introduction and illustrated in ***Figure 1*** (a), the conventional design of a CRIGF is based on a planar waveguide into which two Distributed Bragg Reflectors (DBR) are etched, thereby forming a planar Fabry-Pérot cavity. In addition, a grating in/out-coupler (GC, whose period, Λ_{GC}, is twice the period of the DBR, Λ_{DBR}) is inserted at the centre of the resonator. Technologically, both gratings are made at once and thereby have the same etch depth since this permits to avoid a second challenging processing stage whose the re-alignment would need to be of nanometric precision. (Unetched) Phase Sections (PS) of equal length separate the GC from each of the DBRs.



(a) (b)

Figure 1. (a) Schematic of conventional CRIGFs where the arrows indicate how the device operates. (b) Evolution of the Q-factor of a CRIGF as a function of the etch depth of the (DBR and GC) gratings

For filtering applications, the design procedure used so far is described in particular in [6]. It consists in selecting the multilayer stack thicknesses such that the planar waveguide operates in the singlemode regime at the wavelength of operation and behaves as an anti-reflective coating upon surface-normal excitation by a plane wave. Under the assumption of a fully etched grating layer, the grating periods of DBRs and of the GC can be set as well as the number of DBR etched lines to provide high reflectivity (and, equivalently, a high intrinsic Q factor for the Fabry-Pérot resonator). Using the Fourier Modal Method [13], [14], the GC fill factor and number of grating teeth are then chosen to reach the targeted filtering bandwidth, while the phase section length is selected to maximize the reflectivity at resonance. By extension, such a design applied to a device embedding a $LiNbO_3$ waveguide core led to the first demonstration of nonlinear conversion in CRIGFs in the form of continuous-wave second harmonic generation (SHG) [11].

Taking as an incentive the optimization of the SHG efficiency and its associated change of the relevant figure-of-merit, we have, since then, investigated alternative CRIGF designs, all based on a strategy aiming to maximize the internal field at the pump wavelength in singly-resonant structures.

As a first step, we evaluated the device loaded Q factor, Q_{TOT}, as a function of the (SiN_x) grating etch depth, keeping constant all the other parameters (thickness of the $LiNbO_3$ layer (300 nm), number of grating lines in the GC (11) and DBR (200), phase section length scaling factor ($L_{PS} = 1.125\ \Lambda_{GC}$)). As shown in Figure 1 (b), low Q_{TOT} are obtained for both shallow and deep gratings and an optimum arises for an intermediate etch depth (of ~32 nm). As for other resonators (whispering-gallery-mode resonators, photonic-crystal cavities), this overall performance metric compounds contributions from the intrinsic Q-factor, Q_i, of the GC-free Fabry-Pérot resonator and from the GC coupling Q-factor, Q_c, according to the $1/Q_{TOT} = 1/Q_i + 1/Q_c$ relationship. Analysis of the Q_{TOT} factor at the two etch depth extremes shows that the limitation originates respectively from the weak DBR reflectivity (i.e. low Q_i) associated with shallow gratings and from the excessive in/output coupling (low Q_c) occurring when using deep gratings. The optimum Q-factor corresponds to the situation where the coupling Q factor matches the intrinsic Q factor, i.e. occurs at the so-called critical-coupling condition.

The main drawback of the above-described optimization approach, apart from the experimental difficulty in fabricating structures including a layer of graded/stepped thickness, is that the adjustment parameter simultaneously modifies the two contributions of the loaded Q-factor.

A more suitable method would consist in being able to tune the coupling Q-factor for a fixed (and maximal) intrinsic Q-factor. A way of doing so relies on using a GC whose base pattern can be parametrically modified to adjust the modulus of the coupling Fourier coefficient of its permittivity function (i.e., in most cases, to tune its first-order diffraction term). The simplest implementation consists in changing the GC fill factor but, once again, the corresponding practical demonstration would be rather challenging (especially for high Q_i cavities) as this would entail making (a periodic set of) high-aspect-ratio grooves (or bumps) whose width should be precisely controlled down to a few nanometers. To overcome the latter limitation, we proposed to exploit “bi-atom” GC patterns and numerically showed that the device performance at the pump wavelength but also at the SHG wavelength can be significantly improved [15]. Alternatively, yet another way of tuning the effective coupling efficiency is to shift the GC lines with respect to the (GC-free) Fabry-Pérot mode spatial distribution. Although originally introduced and experimentally validated in [16], we have recently shown, through theoretico-numerical analysis, that this approach should be amenable to achieving extremely high Q-factors ($Q_{TOT} > 10^8$), should it be combined to an apodization scheme in the phase shift sections [17] to avoid the so-far-neglected scattering losses at the GC/DBR interface. Furthermore, we also confirmed in that study that the maximum intra-cavity intensity, hence the maximum SHG conversion efficiency (in the undepleted pump scenario), happens when the resonator is operated at the critical coupling condition.

3. EXPERIMENTAL DEMONSTRATIONS

Having theoretically established different viable routes to create CRIGFs with parametrically adjustable coupling, two sets of devices have been fabricated to respectively test the bi-atom CRIGFs and the asymmetric (also referred to as dark-mode) CRIGFs.

The device fabrication followed the previously reported process flow [6], [11] starting from a 300-nm-thick X-cut $LiNbO_3$ layer on a fused silica substrate. The thickness of the silicon nitride grating layer (and etch depth) was 70 nm and the grating lines 20-µm-long oriented along the $LiNbO_3$ crystalline Z-axis. The GC included 21 lines in "asymmetric GC" set.

The devices linear and nonlinear characteristics were measured using the setup schematically represented in ***Figure 2***. The excitation beam was set to match the GC size and the polarisation to excite the TE-polarized mode of the device.

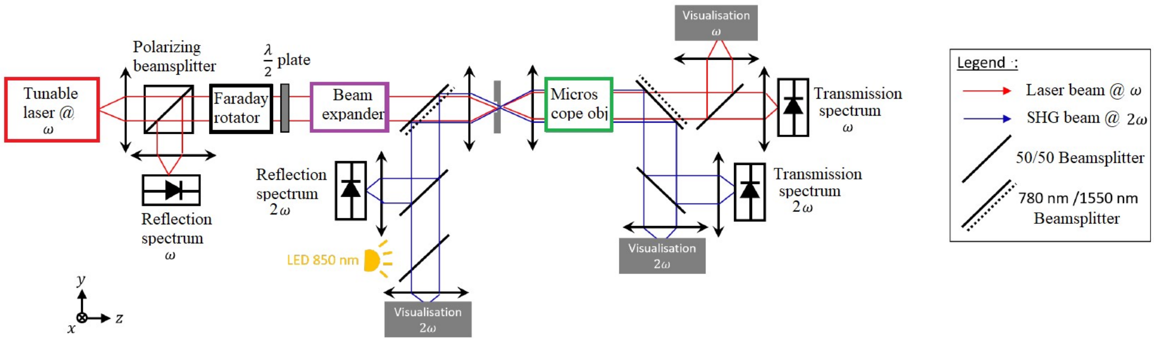


Figure 2. Characterization setup used to measure the pump and SHG signal response of the fabricated CRIGFs

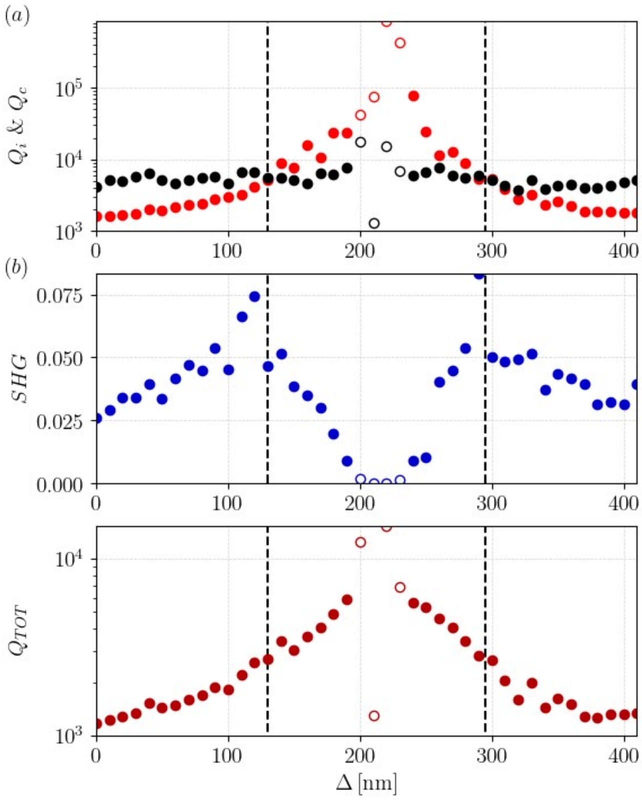


Figure 3. Responses at the pump and SHG wavelengths of asymmetric CRIGFs and extracted evolution of the extracted Q factors as a function of the GC spatial shift.

Analysis of the measured responses at the pump signal was performed based on a modified version of the Fano-resonance model originally proposed by Yoon [18] to fit the characteristics of Guided Mode Resonance Filters (GMRFs). We introduced an additional term in this model to include the fact that there is a spatial overlap mismatch between the excitation beam and the CRIGF intra-cavity mode profile. In the absence of the latter term, the extracted intrinsic Q-factors were found to be underestimated and, as result, it was not possible to explain of the observed conditions leading to optimal SHG (shown in ***Figure 3***) in contrast to the new version which successfully attributes the latter to critical coupling.

We note that although the fabricated bi-atom devices were working, a more extensive set of devices will need to be made to be in a position to match the GC band edge wavelength with the Fabry-Perot resonance for each bi-atom pattern as highlighted in [15].

4. CONCLUSIONS

We have introduced a set of singly-resonant Cavity-Resonator Integrated-Grating filters designs where the coupling rate can be parametrically adjusted without modifying the intrinsic resonator Q-factor with a view to improve the cavity-enhanced Second Harmonic Generation conversion efficiency. Corresponding devices were fabricated and their experimental assessment and analysis using an adapted Fano-resonance fitting model allowed to show that operation at critical coupling was achievable and led to maximal SHG.

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