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Review on Cavity-Resonant Integrated Grating Filters

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ABSTRACT

We review the investigations that have been carried out over the past decade on waveguide Fabry-Pérot microcavities with an embedded input/output grating coupler, devices often referred as Cavity-Resonant Integrated Grating Filters (CRIGFs). We will explain how the device geometry and use of various technological platforms (SiON, LiNbO₃ on insulator, GaAs) has permitted the fabrication of spatially-localized wavelength filters that can operate from the near-infrared to mid-infrared, subsequently enabling applications as laser spectral stabilization or as pixelated filter for (hyperspectral) imaging. Furthermore, we will show that the design can be adjusted to obtain critically-coupled high-quality factor microresonators with a view to induce efficient second harmonic generation or, more generally, nonlinear parametric conversion. Finally, we will present our most recent investigations that have been devoted to the selective excitation of the supported higher order spatial modes and how the latter can be used to implement reconfigurable logical gates.

Keywords: guided-mode-resonance filters, optical filters, micro-resonators, wavelength stabilization, selective modal coupling

1. INTRODUCTION

Cavity-Resonant Integrated Grating Filters (CRIGF) are optical devices constituted, in their most conventional geometry (see Figure 1), of a waveguide grating coupler surrounded by two Distributed Bragg Gratings (DBR) and cavity-length-adjusting Phase Sections (PS)^{1,2}. They were originally introduced in 2012 by Professor Ura's group from Kyoto Institute of Technology with a view to provide efficient and wavelength-selective waveguide coupling of free-space-incoming surface-normal-impinging focused beams^{1,3}. By design, the above-mentioned sub-wavelength grating heterostructure relies on low-refractive-index-contrast features, thereby these optical resonators exhibit a typical cavity length of tens of wavelengths, an intermediate value between the (sub)-wavelength size of photonic crystal nano-cavities and the hundreds-of-wavelengths length of whispering gallery mode (disk, ring) waveguide microresonators.

In this article, we present a short review of the theoretical and experimental challenges associated with the study of such meso-scale resonators and show how to draw out the assets of this geometry to implement not only spectral but also modal selective filtering for potential applications in laser stabilization, hyperspectral imaging, or spatial division multiplexing.

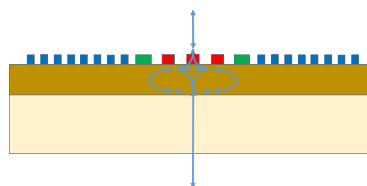


Figure 1. Schematic cross-section of the most common geometry of a Cavity-Resonator-Integrated Grating Filter where the substrate is in pale yellow, the waveguide core layer is in brown, and the red, green and blue lines constitute respectively the grating coupler, the phase section and the Distributed Bragg Reflectors. The arrows indicate the optical pathways within the device.

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2. DEVICE DESIGN AND SIMULATIONS

As shown in Figure 1 and mentioned in the introduction, CRIGFs are based on waveguide grating coupler surrounded by two Distributed Bragg Gratings (DBR) and two Phase Sections (PS). The grating period in the GC and DBR sections are respectively λ/n_{eff} and $\lambda/(2*n_{\text{eff}})$ where λ is the filter resonant wavelength and n_{eff} is the (local average) effective index of the corrugated waveguide. The PS are typically unetched sections whose length is chosen to adjust the GC position with respect to the cavity modes established between the two DBRs⁴. The choice of the grating depth controls simultaneously the in/outcoupling strength of the GC and the interfacial reflection within the DBRs. To induce a wavelength-selective coupling behavior from the GC, a shallow grating depth would be preferred but the latter has to be traded-off against narrow stopband reflection from long DBRs⁵. The grating fill factor in the DBR is typically taken to be ~ 0.5 while, in the GC, this parameter offers an additional degree of freedom to adjust the coupling strength (although it is often set to 0.5 too).

Given the above 2-dimensional nature of CRIGFs, their design and performance simulations were initially performed using the Finite-Difference Time-Domain FDTD method^{1,2} as this approach was commonly used to model a variety of established nanophotonic devices including photonic crystal cavities and dielectric waveguides.

Alternatively, recognizing that these devices are built from periodic structures, the Rigorous Coupled-Wave Analysis (also referred as Fourier Modal Method) has also been widely used to predict the characteristics of these devices. In this case, the full structure (see Figure 1) is considered as a periodic unitary (super)-cell and the undesirable cross-device coupling induced by periodic folding is suppressed thanks to the addition of appropriate PMLs on either side of the DBR sections⁶.

Finite Element Modelling (FEM) was also successfully used to calculate the spectral response of CRIGFs⁷.

In all three cases, it should be emphasized that the low contrast in the effective refractive index between the various grating parts (teeth and troughs) of the CRIGFs means that the optical interactions need to be taken into account with deep sub-wavelength resolution over dimensions of several hundreds of wavelengths. As a result, these calculations tend to be computer intensive either in terms of time or memory⁷. A typical Fano-resonance reflectivity/transmission spectra of a CRIGF designed to operate at ~ 1550 nm whose spatially-centered GC is excited by an Gaussian beam of appropriate width² is shown in Figure 2.

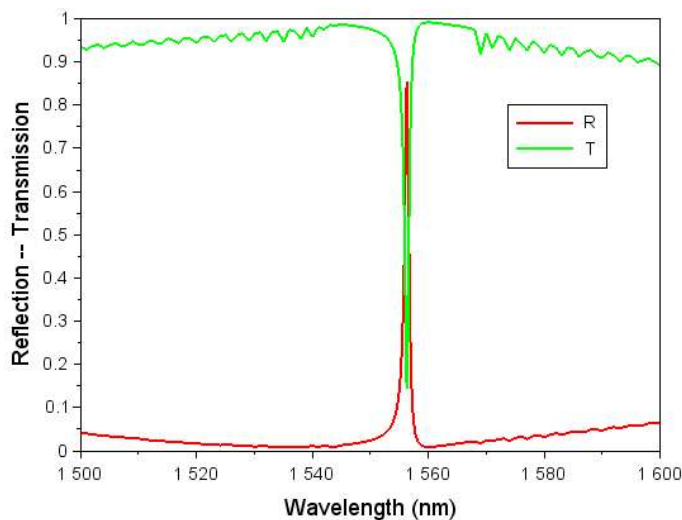


Figure 2. Wide band spectral response of a CRIGF designed to operate at 1555 nm calculated using the RCWA method⁵.

In light of the above calculation considerations, simplified models have also been set up to give further insights into the operating principles of these devices. In particular, the in-plane reflectivity and transmission of the corrugated waveguide structure has been calculated using the Transmission Matrix Method⁸. This approach has specifically permitted to establish that CRIGFs support two sets of modes, the bright and the dark modes whose radiative nature depends on position of their field nodes relative to the sidewalls of the grating coupler⁹. However, the extension of these calculations to compute the full device characteristics under free space illumination happens to be non trivial as it would require the evaluation of the GC out-of-plane coupling contributions, parameters which can only be related to the device geometry through a tricky (yet technically tractable¹⁰) normalization over a semi-infinite space region.

In keeping with the view of analyzing CRIGFs with a simple model, it is helpful to recognize that CRIGFs are effectively transversely-coupled Fabry-Pérot resonators. As result, it was found useful to classify the device as operating in the over-coupled, critically-coupled or under-coupled regime depending on whether the GC-mediated coupling is higher (equal or lower respectively) than the other (internal) losses induced through the propagation in the cavity¹¹. This facilitated the analysis of the performance of various CRIGF designs¹¹ among which one with index-matched phase sections whose (loaded) Q-factors was theoretically found to be greater than 10^6 .

Similarly, to enable the extraction of physically-meaningful parameters from experimental reflection/transmission recordings, a model based on the Coupled-Mode Theory has recently been proposed and validated¹². Combining the last two theoretical aspects, the experimental demonstration of critically-coupled devices with record (loaded) Q-factors of $\sim 10^4$ has been achieved¹². The latter value however points out that the internal losses are still significant and that process improvements to limit them would be welcome. Additionally, that study also emphasized the benefits of matching the supported cavity mode field profile and the excitation beam. To address the latter point, two approaches have been proposed, the former consisting in apodizing the grating structure to shape the supported fundamental mode profile to resemble to a Gaussian distribution^{13,14} and a second method whereby the injected signal is shaped using a spatial light modulator to selectively address the desired cavity mode¹⁵.

3. EXPERIMENTAL DEMONSTRATIONS

Experimentally, the fabrication of CRIGFs typically begins with the deposition of a waveguide core layer on a substrate that is usually transparent at the chosen wavelength of operation. The grating pattern is then created by e-beam lithography and transferred into the waveguide core layer by a partial dry etching step (and the associated removal of the remaining resist). An additional top cladding layer as well as a backside substrate treatment can be subsequently added to induce an anti-reflective (AR) behavior from the (unstructured) multilayer-coated sample. As a further step towards a more widespread uptake and use of these components, a process involving hard mask fabrication of the grating patterns in silicon wafers and subsequent UV-soft-mold lithography replication into the appropriate waveguide has also been developed^{16,17}.

Independently of the chosen fabrication method and contrary to the simulations where the gratings are assumed to be linear and of infinite dimension, the lateral extent of practical devices is typically restricted to three to five times the (GC) cavity longitudinal length to warrant reasonable e-beam writing times. Since the DBRs are commonly based on (finite-lateral-size) linear gratings, the fabricated CRIGFs are marginally-stable optical resonators¹⁸ which may restrict the achievable quality factors. A well-known method to overcome the latter limitation would be to exploit concentric resonators, i.e. make use of curved DBRs as in reference¹⁹ or to introduce an additional lateral optical confinement structure²⁰. Alternatively and as illustrated in Figure 3, this lateral direction offers an extra degree of freedom that can be used, for instance, to implement a periodicity scaling of the base pattern to fabricate filters whose resonance wavelength is spatially graded¹⁶ or to create another orthogonal 1-D CRIGF to obtain a polarization-independent response²¹.

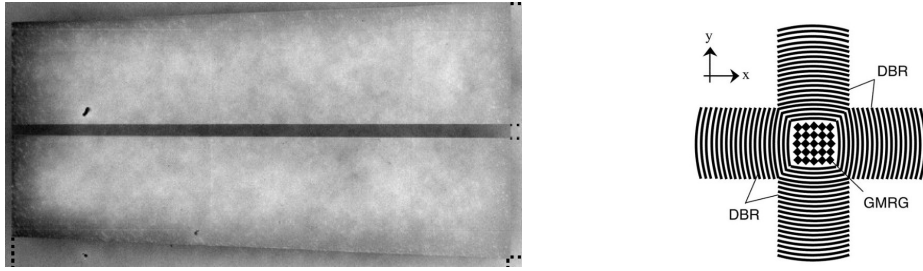


Figure 3. (left) top view Scanning Electron Microscope image of a fan-out-grating spatially-tunable CRIGF¹⁶ and (right) top view diagram of a polarization-independent CRIGF²¹.

Practically, the devices were initially made using silicon nitride waveguides on silica glass substrates, allowing operation in the near-infrared region^{1,2}. To widen the spectral coverage towards the mid-infrared, CRIGFs based on AlGaAs semiconductor alloys epitaxially grown on GaAs substrates have also been reported¹⁷. Typical reflectivity/transmission characteristics are shown in Figure 4 and demonstrate that Fano-like resonant responses with Q factors greater than 10^3 can be obtained in each spectral band.

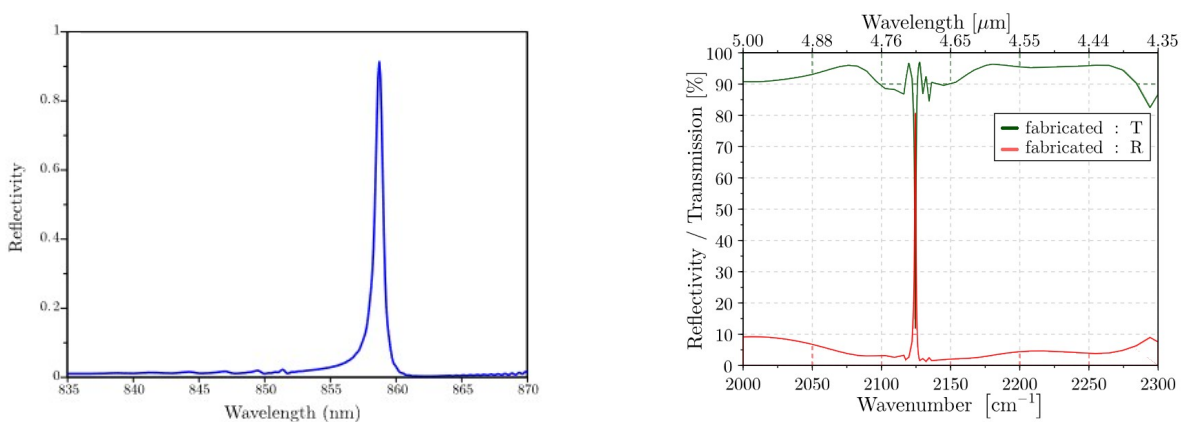


Figure 4. Spectral response of a CRIGF operating in the (left) near infrared² and (right) in the mid-infrared¹⁷.

In all the above-described cases, the fabricated devices exhibit a spectral response that is fixed by the etched grating pattern. To overcome the latter limitation and implement short-range resonant wavelength tuning, it became attractive to consider alternative waveguide and substrate materials amenable to induce a sufficient modification of the waveguide effective refractive index. The lithium niobate on insulator (LNOI) technology was selected on this basis because of its favorable thermo-optic and electro-optic properties and has led to the demonstration of nanometer-range spectral tuning of near-infrared devices^{5,22}.

4. DEVICE APPLICATIONS

As explained in the previous paragraphs, CRIGFs are optical filters that can provide resonant reflection with Q-factors reaching up to $\sim 10^4$ under illumination by a surface-normal impinging beam whose diameter is of the order of ten wavelengths.

Arguably, CRIGFs were originally proposed as efficient wavelength-selective waveguide couplers for Wavelength-Division Multiplexed routing but the proof-of-principle of this initial application was only provided in reference³ in 2018.

To-date, the most prominent and direct use of CRIGFs has been as the wavelength-stabilization element of Extended-Cavity Diode Lasers (ECDLs)^{23–26} and, more recently, of Vertical Extended-Cavity Surface-Emitting Lasers (VECSELs)²⁷. In the near-infrared ECDLs where the CRIGF acts as the output-coupling spectrally-selective mirror, emission with tens-of-milliwatt output and narrow (<200-kHz) linewidth has been obtained^{23,25}. If wide-range tunable

operation has also been made possible by the (intra-cavity) displacement of a spatially-graded CRIGF²⁴, narrow-range electronic-tuning has recently been demonstrated^{5,22} as a step towards laser fine spectral locking on an atomic absorption line for cold (Rb, Cs) atom cooling applications. Apodization of the fundamental cavity mode into a Gaussian beam to enhance the efficiency of the fibre coupling and the integration into the CRIGF of the optical relay lens^{28,29} are two contributions which could eventually lead to even more robust and compact ECDLs. Similarly, the use of CRIGFs with integrated mirror back-coating³⁰ as rear-cavity reflector or the use of CRIGFs operating under oblique incidence^{31,32} may offer valuable alternative configurations for ECDLs. Another yet even more integrated approach would be to incorporate the organic^{33,34} or inorganic^{35,36} semiconductor gain element into the CRIGF structure to directly induce wavelength-selected surface-normal emission. In that case, the device is often referred as mixed-order Distributed FeedBack laser (mixed-order DFB). This gain in compactness might come at the expense of a larger emission linewidth since the latter is essentially controlled by the overall resonator cavity length.

Besides, owing to their resonant energy storage capability and the technological ability to implement CRIGFs into waveguides made of materials presenting high second-order susceptibility (such as the above-mentioned LNOI or GaAs platforms), a few studies of nonlinear parametric conversion into these intermediary-sized resonators have been carried out. In particular, it has been established that Second Harmonic Generation under continuous-wave^{37,38} or femtosecond pulsed³⁹ pumping can be obtained with enhanced efficiency with respect to their bare thin-film or Guided-Mode Resonating Filter counterparts. Future work will certainly focus on the impact of the phase matching condition in these intermediate size converters and on achieving parametric generation using non-degenerate processes.

Moreover, from the above-stated characteristics, CRIGFs can be considered as a particular form of pixelated filters. In particular, the reported spatially-graded architecture¹⁶ provides an alternative route to patterned multilayer thin films to make “stripe” optical filters⁴⁰. However, the uptake has so far been constrained by the fact that bandpass filter operation is only available in reflection mode and not in transmission and because their out-of-band rejection is somewhat limited. Similarly, the current length of the side DBRs prevents them to be used as the elementary constituent of 2D multispectral Bayer-type matrices⁴⁰. This drawback might be alleviated by substituting the latter mirrors by metallic versions as shown in reference⁴¹.

Last but not least, CRIGFs have been shown to be not only spectral filters but also spatial mode filters¹⁵. As such, they may find opportunities in on-chip waveguide routing exploiting spatial division multiplexing of few-mode fiber injection^{42,43} or in performing the linear or nonlinear operations needed in photonic neural networks⁴⁴. In the latter context, the spatio-spectral excitation of multimode CRIGFs has been shown to enable the implementation of reconfigurable logical gates⁴⁵.

5. CONCLUSION

We have reviewed a decade of investigations of Cavity-Resonant Integrated Grating Filters including aspects of design, performance simulations, as well as device fabrication, characteristics and potential applications. In particular, these low-index contrast grating heterostructures constitute a class of pixelated optical filters that are ideally suited for excitation with focused beam of tens-of-wavelength spot size and that can offer spectrally and spatially selective resonant response whose loaded Q-factor can reach values of up to $\sim 10^4$ at any wavelength within the 0.7 to 5- μm range. These features have been exploited in a variety of proof-of-concept application demonstrators such as wavelength-selected waveguide couplers, wavelength-lockers of extended-cavity lasers, nonlinear parametric converters as well as logical gates.

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