Analysis in reciprocal space of the band-pass filter effect in uniform and non-uniform grating couplers

L Zagaglia, F Floris and P O’Brien
Tyndall National Institute, Lee Maltings Complex, Dyke Parade, T12R5CP, Cork, Ireland
E-mail: luca.zagaglia@tyndall.ie

Abstract. A detailed study on the origin of the bandwidth reduction in the Coupling-Efficiency (CE) spectrum for non-uniform grating couplers (nu-GCs) due to a band-pass filter effect is reported. This effect is deeply investigated through Finite Difference Time Domain simulations (FDTD) in order to look at the spatial Fourier Transform (sFT) of the nu-GC’s emission, which gives the energies and the wavevectors sustained by the overall structure. We show: how to evaluate the bandwidth from the sFT and how the band-pass filter effect arises from the sFT affecting the CE spectrum giving a physical insight on the bandwidth’s reduction. Moreover, we also point out how the concept of photonic crystal bandstructure can be applied for such nu-GCs and used as a powerful tool to describe the dispersion of the light inside these non periodic structures. Finally, both the sFT and the bandstructure approaches are shown to give the same outcomes in terms of the bandwidth evaluation and to be in agreement with the CE spectra’s behaviours. The entire analysis is proposed also for uniform-GC in order to directly compare the two different types of structures.

1. Introduction

Grating-couplers (GCs) are one of the major structures used to efficiently couple in and out the light from Photonic Integrated Circuits (PICs) with quite relaxed alignment tolerances [1, 2]. Fig.1 panel (a) represents a generic three dimensional GC structure with the etched pattern developed along the x-direction. Considering a cross section along x, two main types of GCs can be distinguished: uniform-GCs (u-GCs), i.e. the pitch Λ is constant across the structure, and non-uniform GCs (nu-GCs), i.e. the pitch Λ(𝑥) varies linearly, as shown in panel (b) and (d).

As already demonstrated in literature [3, 4], a varying pitch and a higher GC layer, respect to the standard thickness of 220nm, improve the performances of the GC in terms of its Coupling-Efficiency (CE), which is the amount of light coupled into the PIC at a specific working energy E. For example, a u-GC with a GC layer thickness of 220nm can reach a CE = 60% at the working energy of 0.80eV, which corresponds to a wavelength of 1550nm (C-band in telecom applications); while a nu-GC with a GC layer thickness of 290nm exploits a maximum CE of 85% at the same working-energy, as shown in the two CE spectra in panels (c) and (e) evaluated using Finite Different Time Domain (FDTD) simulations. However, the maximum CE is not the only parameter used to quantify the quality of the coupling-process; also the bandwidth (BW) (i.e. the energy, or wavelength, interval associated with the drops from the CE apex of the 80% of its value) is a fundamental parameter that characterized the CE spectra and, actually, the limited BW represents one of the major disadvantages of these type of structures in some applications [5]. So, while the u-GC has a BWu-GC = 45nm, the nu-GC has a bandwidth of...
Figure 1. a) Generic Grating-Coupler (GC) structure on a Silicon-on-Insulator (SOI) platform. The grooves are developed along the x-direction. b) Cross-section view of a uniform-GC (u-GC), the pitch $\Lambda = \text{constant}$, taken along x. Three layers can be distinguished: the Si substrate at the bottom, the SiO$_2$ bottom oxide in the middle, and the Si GC layer. c) Coupling-efficiency (CE) spectrum, evaluated using the Finite Difference Time Domain (FDTD), of a u-GC with a GC layer thickness of 220nm tuned at $E=0.80\text{eV}$ (corresponding to $\lambda=1550\text{nm}$) for an impinging angle of $\theta=10^\circ$. The CE at 0.80eV is 60% with a bandwidth $\text{BW}=45\text{nm}$. d) Cross-section view taken along x of a non-uniform GC (nu-GC), the pitch $\Lambda$ changes linearly with x. d) CE spectrum of a nu-GC with a GC layer thickness of 290nm tuned at $E=0.80\text{eV}$ and $\theta=10^\circ$. The CE at 0.80eV is 85% with a $\text{BW}=30\text{nm}$. $\text{BW}_{\text{nu-GC}}=35\text{nm}$ resulting in a reduction of 15nm, or equivalently a percentage difference of the 35%. Moreover, the two spectra have another fundamental difference: the nu-GC spectrum is asymmetric around the 0.80eV where a sharper decay affects the higher energy regions respect to the more “gentle” behaviour shown at the lower energies. The reduced BW and the asymmetric shape are consequence of the non-uniform pitch, which introduces a band-pass filter effect that asymmetrically filter out the energies around 0.80eV in a more selective way respect to a u-GC. At the best of our knowledge, no one has tried to deeply explain and investigate this filter-effect mostly because: (i) the interaction between light and matter in such structures is not trivial to model and (ii) usually the design and optimization of GCs is done through a “black-box” approach. Iterative-algorithms, such as Particle Swarm, or Genetic Algorithms, implemented inside a computational-method, such as the FDTD, are used to randomly change the geometrical features of the structure in order to maximize the CE at the working wavelength [4, 5]. In this paper, we use FDTD simulations to investigate the band pass filter effect looking at the differences in the dispersion of the light in the u- and nu-GC resorting to: the spatial Fourier Transform (sFT) of the electromagnetic field (EM) emitted by the two GCs and the concept of photonic-crystal (PC) bandstructures [6].

2. Bandpass filter effect
The nature of the BW in a u-GC has been already explained in [5] and an analytic formula has already been derived using the rigorous grating theory [7]. Briefly, when we are in the Gaussian-
The u-GC and nu-GC have been rebuilt inside the FDTD software [8], a mode-source [9] is used to inject, through the waveguide fundamental mode, the light into the simulation, and finally a “field and power” monitor [10] is utilized to collect the EM field scattered out by the GCs. The sFT obtained by the EM fields are reported in panels (a) and (d) of Fig.2, respectively for the u-GC and the nu-GC.

The u-GC sFT exhibits a linear relation between the energies and the wavevectors $K_x$, which remains the same throughout the entire energy interval. The associated broadening in energy is homogeneous and symmetric along the entire sFT suggesting an equal behaviour for all the energies sustained by the u-GC. On the contrary, the nu-GC sFT has two well-defined “stopband” regions at the borders of the energy interval (i.e. 0.75eV and 0.85eV), where the sFT plot regime [5], the BW is the projection onto the energy interval associated with the overlap-region between the incoming-light line, which has a natural ΔK broadening, and the bandstructure (i.e. dispersion relation) of the u-GC, which is a dielectric periodic structure and hence it can be treated as a one dimensional PC. We assume a Gaussian-regime in our study, as our light source is represented by the emission of a single mode fiber with the usual $1/e^2$ intensity mode field diameter (MFD) of 10.40μm at E=0.80eV ($\lambda=1550$nm). However, a nu-GC is not periodic and the concept of PC bandstructures cannot be transposed directly to it. Therefore, an alternative and straightforward way to investigate the dispersion of the light, using the energies and the wavevectors supported by the GCs, is to consider the sFT of the EM field scattered out in the near-field region of the GCs.

2.1. Fourier Transform approach

The.u-GC and nu-GC have been rebuilt inside the FDTD software [8], a mode-source [9] is used to inject, through the waveguide fundamental mode, the light into the simulation, and finally a “field and power” monitor [10] is utilized to collect the EM field scattered out by the GCs. The sFT obtained by the EM fields are reported in panels (a) and (d) of Fig.2, respectively for the u-GC and the nu-GC.

The u-GC sFT exhibits a linear relation between the energies and the wavevectors $K_x$, which remains the same throughout the entire energy interval. The associated broadening in energy is homogeneous and symmetric along the entire sFT suggesting an equal behaviour for all the energies sustained by the u-GC. On the contrary, the nu-GC sFT has two well-defined “stopband” regions at the borders of the energy interval (i.e. 0.75eV and 0.85eV), where the sFT plot
deviates from its linear behaviour and the slopes tend to zero delineating a precise energy working-window, like a filter. Furthermore, the broadening of the sFT is not symmetric and homogeneous any more, but it increases going from the higher energies to the lower ones defining a up-right narrower region and a down-left thicker region. As a consequence, if we consider a fixed value of $K_x$, the nu-GC filters the energies asymmetrically around the apex of the associated sFT cross-section. Both the u-GC and nu-GC have been tuned to couple an EM field at $E=0.80\text{eV}$ with an impinging angle of $\theta=10^\circ$, hence the structures are optimized to couple the in-plane wavevector component $K_x = \frac{2\pi}{\lambda}E(eV) \cdot \sin(\theta) = 1\mu m^{-1}$, in accordance with the Bragg relation [2].

Considering two cross-sections at $K_x = 1\mu m^{-1}$, the one dimensional sFTs represented in panels (b) and (d) of Fig.2 can be obtained. From the spectral widths of the two sFTs, the BWs of the associated structures can be re-evaluated as in the CE spectra: 45nm and 30nm for the u-GC and for the nu-GC respectively. The symmetric and asymmetric behaviours around the apexes of the curves are more visible here showing how the nu-GC filters sharply the higher energies sustaining better the lower ones, in accordance with the behaviour displayed in the CE spectrum.

The sFTs give the overall response of the entire structures in terms of energies and wavevectors; however, not all the energies and the wavevectors in panel (a) and (d) are involved in the coupling process. To look at the energies and $K_x$ that are actually coupled, the overlap sections between the sFT and the source’s sFT have to be considered, as shown in panels (c) and (f) of Fig.2. Here, the overlap region in the u-GC case displays a linear behaviour with an homogeneous and symmetric broadening in agreement with the previous results; while an inhomogeneous and asymmetric shape characterized the overlap region in the nu-GC case as a consequence of the band-pass filter effect.

### 2.2. Bandstructure approach

The FDTD method can be used to calculate the PC bandstructure around a certain interval of energies [11], as shown in panel (a) of Fig.3 where a picture of the simulation box has been reported.

Panel (b) shows the calculated bandstructure for the u-GC, around the 0.80eV, and the spreading in $K_x$ of the incoming-light line dispersion associated with the impinging EM field. The projection on the energy axis of the intersections points between the bandstructure line and the incoming-light line gives the bandwidth limits (i.e. the maximum (MB) and the minimum (mB)); thus, doing MB-mB a bandwidth of 45nm is again calculated. Instead, the nu-GC can be considered as composed at each period by a u-GC with its own pitch $\Lambda_i$, which characterizes locally the propagation of the EM field travelling inside the GC layer. The overall band-pass filter effect is then the final result of the light going through the local u-GCs that exploits its own bandstructure dispersion. To investigate this, as shown in panel (c), the bandstructures of each u-GC, which composes the nu-GC, have been calculated and the behaviours around 0.80eV are reported in panel (d) for the first, fifth, tenth and fifteenth periods, in order to cover the entire region of the nu-GC that is actually shined by the incoming EM field. Now, three main energy regions can be defined by the overlap between the incoming-light line and the multiple bandstructure lines: the filtered out energies, the bandwidth, and the spectrum asymmetry.

We set the MB value as the intersection point between the incoming-light line and the blue bandstructure line related to the first period. This coincides also with the minimum of the filtered out energies section; in fact, the light that has been coupled travels inside the nu-GC towards the first period, which can sustain a maximum energy given by the MB point. Even if higher energies are permitted at different periods, due to multiple-intersection points, those energies are filtered out by the varying pitches of the locally u-GC during the propagation process.
Figure 3. a) Set-up sketch of the FDTD simulation used for bandstructure evaluation for the u-GC. b) Overlap-section between the bandstructure-black line around E=0.80eV and the incoming-light line dispersion, in pink, with its related Kx spreading. The projection of the overlap onto the energy axis gives a BW=45nm. c) Bandstructure evaluation for every u-GC that composes each period of the nu-GC. The two sketches show the differences between the FDTD simulation boxes at different periods. d) Overlap-sections between the bandstructure lines around E=0.80eV and the incoming-light line dispersion for the first (blue), fifth (grey), tenth (brown), fifteenth (orange) periods. Three regions can be identified: the filtered out region, the BW=30nm, and the spectrum asymmetry region.

inside the GC layer. Thus, a filtered out energy region can be defined. This is in accordance with the sharp decay seen in the higher energies for the sFT cross-section plot and the CE spectrum. The mB point has been fixed as the intersection between the incoming-light line and the tenth period, corresponding to the brown bandstructure line. The tenth period is the most important in terms of the scattering process that couples the light into the nu-GC. The SMF Gaussian mode shines with its “center of gravity” on the tenth period. This means that the majority of the energies coupled into the nu-GC come from the interaction between the incoming EM field and the tenth tooth. As a consequence, a mB point can be identified and used to estimate the width of the BW as MB-mB= 30nm. This value is in accordance with the previous evaluation of the CE spectrum.

The last energy region considered (spectrum asymmetry region) in Fig.3 panel (d) affects the decay of the sFT cross-section and the CE spectrum at lower energies. The tail of the impinging Gaussian mode is scattered by the periods from the ninth up to the first one. Here, the minimum sustained energy is given again by the intersection between the incoming-light line and the bandstructure line of the first period; however, there is not any more a single intersection point, as before. In fact, the first period defines a lower limit and all the energies above it are allowed to travel in the nu-GC region; so, a selective filtering-effect does not take place any more. Moreover, the slopes of the curves start decreasing and becoming different reaching the band-edge region of the bandstructures. As a consequence, the intersection points are not separate by the same width in terms of energies (e.g. the distance between the intersection points of the first and the fifth periods is not equal to the one between the fifth and the tenth). This affects the CE
spectrum resulting in a wider width due to a more “gentle” decay at the lower energies. This more complex situation, due to the multiple intersection points, creates the band pass filter effect and affects the final shape of the CE spectrum.

3. Conclusion
A detailed computational study, using the FDTD method, of the BW reduction in nu-GC, respect to the u-GC, due to a band pass filter effect has been proposed. We have shown how the shapes of the sFTs for both structures can be used to investigate deeply the propagation of the light looking at the energies and wavevectors supported. The inhomogeneous and asymmetric behaviour displayed by the sFT of the nu-GC suggests the arise of a band pass filter effect, which affects selectively and differently the higher and lower energies around $E=0.80\text{eV}$, corresponding to a wavelength of $1550\text{nm}$ (C-band in telecom applications). Considering a cross-section of the sFTs at the fixed value of $K_x=1\mu m^{-1}$, related to an incident angle $\theta=10^\circ$, a $\text{BW}_{u-GC}=45\text{nm}$ and $\text{BW}_{nu-GC}=30\text{nm}$ have been re-evaluated in accordance with the CE spectra with a percentage difference around 35%. Moreover, we have shown how the bandstructure concept can be extended to the nu-GC case. The behaviours of the bandstructures are used to compare in details: (i) the dispersion of the light inside the two different GCs and (ii) the features of the CE spectra re-evaluating the BWs, again in accordance with the $\text{BW}_{u-GC}$ and $\text{BW}_{nu-GC}$ values. Thus, the bandstructures have been demonstrated to be a powerful tool to explain the physical cause of the band pass filter effect. In future, these approaches could be implemented inside a GC’s optimization-procedure in order to gain control on the BW and tailor it.

Acknowledgments
This work was supported by Science Foundation Ireland (SFI) under Grant 12/RC/2276.

References
[1] Carroll L. et al. 2016 Appl. Sci. 6 426(1).
[2] Marchetti R, Lacava C, Carroll L and Gradkowski K and Minzioni P 2019 PHOTONICS RES. 201
[3] Bozzola, A, Carroll L, Gerace D and Cristiani I and Andreani L C 2015 Opt. Express. 23 16289
[4] Marchetti R, Lacava C., Khokhar A, Chen X, Cristiani I, Richardson D J, Reed G T and Petropoulos P and Minzioni P 2017 Sci. Rep. 7 16670(1).
[5] Passoni M, Gerace D and Carroll L and Andreani L C 2017 Appl. Phys. Lett. 110 041107(1).
[6] Joannopoulos J D, Johnson S G and Winn J N and Meade R D 2008 Photonic Crystals: Modelling the Flow of Light (New Jersey: Princeton University Press)
[7] Xiao Z, Liow T-Y, Zhang J and Shum P and Luan F 2013 Opt. Express. 21 5688
[8] Lumerical Inc.: http://www.lumerical.com/tcad-products/fdtd/ (accessed on 14 June 2019)
[9] https://kb.lumerical.com/ref_sim_obj_sources_integrated_mode_source.html (accessed on 14 June 2019)
[10] https://kb.lumerical.com/ref_sim_obj_monitors_frequency_domain_field.html (accessed on 14 June 2019)
[11] https://apps.lumerical.com/diffractive_optics_waveguide_pcbandstructure.html (accessed on 14 June 2019)