Beyond traditional bandwidth tunability in grating-assisted couplers: enhanced design techniques and theoretical limitations

(Article begins on next page)

Beyond traditional bandwidth tunability in grating-assisted couplers: enhanced design techniques and theoretical limitations

Lorenzo Tunesi[a], Andrea Carena[a], Vittorio Curri[a], and Paolo Bardella[a]

[a]Department of Electronics and Telecommunications, Politecnico di Torino, Turin 10126, Italy

ABSTRACT

Grating-Assisted Contra Directional Couplers (GACDCs) are versatile photonic devices used to implement add-drop responses with unlimited free-spectral range, steep roll-off and low ripple: due to these properties, GACDC are suitable integrated solutions for Wavelength Division Multiplexing (WDM) systems and many other applications transparent optical spectral processing. Different design techniques can be deployed to optimize their static response, with thermal control being used to dynamically adjust the drop bandwidth, allowing for further implementation flexibility. A new design technique that involves altering the periodicity of the gratings (pitch chirping) can enhance the dynamic control, leading to much wider bandwidth tunability without changing the required control scheme. In this work, we investigate the limits of such technique, highlighting the advantages through simulation of both the optical response as well as the thermal control.

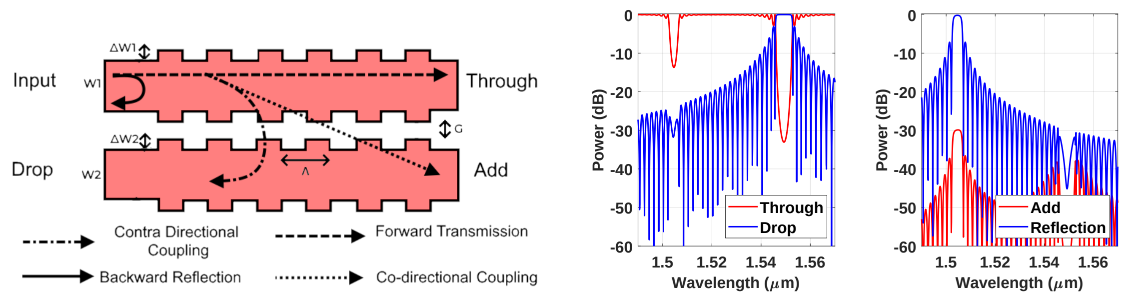
Keywords: Grating Assisted Couplers, Bragg Grating, Add-Drop Filters, Bandwidth flexible

1. INTRODUCTION

The field of Photonic Integrated Circuits (PICs) is expected to see a rapid increase in the coming years, due to the high performance capabilities and cost-effectiveness introduced by integration, as well as the wide range of applications[1] that benefit from it. Moreover, the rise in flexibility and programmability in PICs has transformed photonics into a fundamental enabling technology, not only for optical communications, but also in many adjacent fields, such as computing, quantum, sensing, and biomedical.[2]

In this work, we focus on their application to telecommunications, which benefits from reconfigurable switching and filtering structures, capable of dynamically allocate and route different spectral regions toward the desired output. Multiple photonic components can be used to implement frequency-selective filtering elements, such as Micro Ring Resonators (MRRs),[3] Mach-Zehnder Interferometers (MZIs),[4] Arrayed Waveguide Gratings (AWGs), and many more, but this work focuses on Grating-Assisted Contra Directional Couplers (GACDC), due to their wide design space and spectral properties. GACDCs are versatile structures capable of implementing many different functionalities ranging from reflectors, mode and polarization multiplexers/converters,[5] and frequency selective add-drop filters.[6] GACDCs share their principle with traditional Bragg reflectors, leveraging the distributed grating structure to precisely control field coupling and longitudinal evolution.[7] In their application as WDM multiplexers / demultiplexers (MUX / DEMUX)[8] they are used due to their wide-band flat-top profile with steep roll-offs. Moreover, GACDCs can also be dynamically controlled to tune their 3 dB bandwidth and central operating wavelength, making them a candidate component for elastic networks. This dynamic control can be implemented through different means, with thermo-optic tuning being the traditional and most common method: by leveraging the thermal dependency of the semiconductor properties, the field propagation in the waveguide can be dynamically modified. This work explores the range in dynamic control available through thermo-optical means, investigating the design techniques which can increase the tuning range, highlighting the limiting factor and feasibility of the control scheme.

Further author information:
P. Bardella: E-mail: paolo.bardella@polito.it L. Tunesi: E-mail: lorenzo.tunesi@polito.it



(a) (b)

Figure 1: **(a)** Generic GACDC geometry highlighting the main coupling effects for the input signal. **(b)** Typical frequency response at the four ports of a GACDC (the reflection peak represent the signal reflected backwards from the input port).

2. GACDC DESIGN PRINCIPLE

GACDCs are four-port integrated photonic components characterized by a periodic index perturbation in an otherwise uncoupled asymmetric two-waveguide system. The structure consists of two waveguides with different core width, whose side walls are periodically corrugated, generating a grating structure Fig. 1a. The gratings introduce frequency-selective coupling between the forward-propagating mode of the input waveguide and the backward-propagating mode of the second waveguide, leading to the contra-directional coupling: the waveguide asymmetry and gap are instead designed to limit the co-directional coupling.

The operating principle behind this coupling is based on Bragg gratings,[9] which act as distributed wavelength-selective mirrors along the propagation direction, for a wide range of frequency responses[10] based on the waveguides cores and the corrugations geometries. The grating periodicity, together with the effective index of the propagating modes, defines the phase match condition between the forward and backward waves, i.e the channel wavelength, while the corrugation geometry affects the modal overlap, which defines the coupling coefficient.

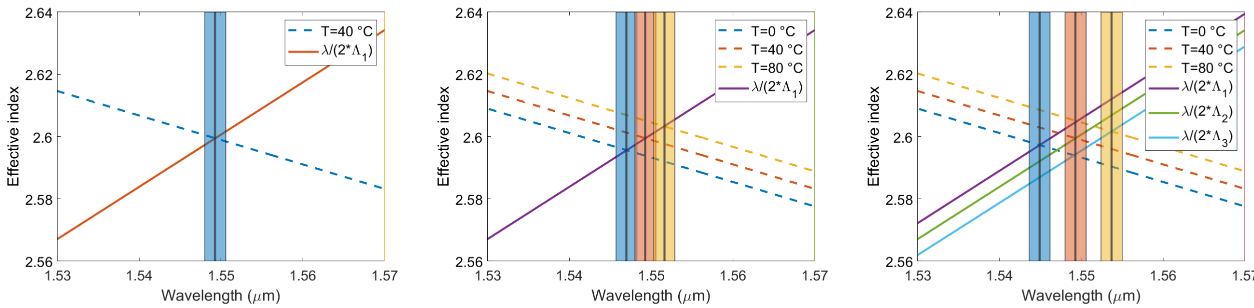
In the typical response of a GACDC device, depicted in Fig. 1b, four main effects can be identified. The gratings introduce backward reflection inside the waveguide, leading to a small reflection peak in the response; the two gratings introduce contra-directional coupling at the target frequency, which is routed toward the drop port. Finally, the rest of the spectra propagates toward the through port, while some parasitic co-directional coupling may arise toward the add port.

As a reciprocal device, while the target spectrum is dropped from the input toward the Drop port, the same wavelength-dependent filtering is present from the Add port, which allows multiplexing the channel back onto the main waveguide.

Apart from the central frequency and bandwidth, the spectral properties of GACDCs can be improved through optimal design techniques, which allow the reduction of parasitic effects, such as the intra-waveguide reflection as well as the ripples and side-lobes. Instead of abruptly introducing the grating, the transition from the intrinsic waveguides can be smoothed out, by introducing apodization: this severely reduces the ripples, allowing higher extinction ratio and lowering cross-talk. A second typical design technique is the shift between the grating profiles on the side of each waveguide:[11] this 180°, or out-of-phase, profile severely reduces the intra-waveguide reflection, removing the spurious reflection peak seen at the input port.

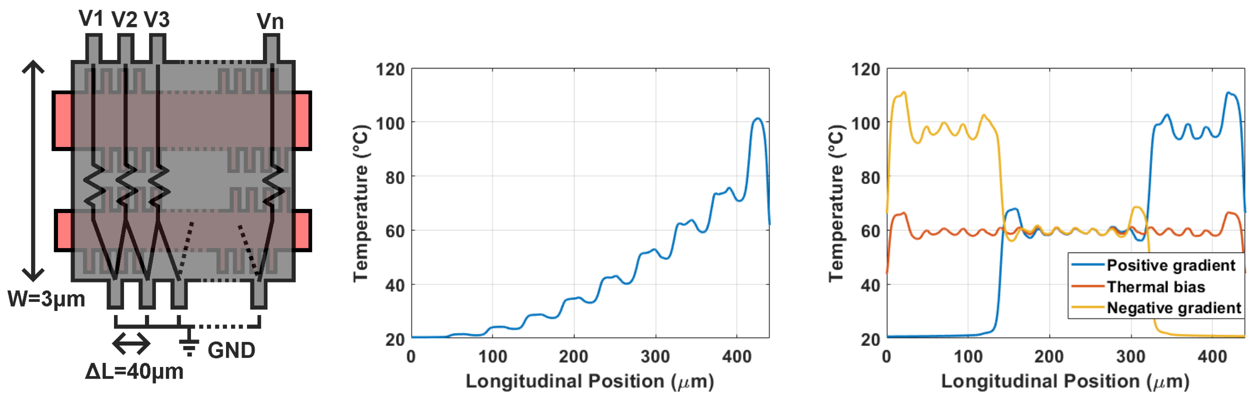
Lastly, the bandwidth of the device can be increased by chirping of pitch, slowly varying the periodicity along the longitudinal direction, which introduces multiple phase-match conditions acting as a cascaded device.

All the above design techniques have been considered for the reference device, which is used as a benchmark for the subsequent analysis: the waveguide and grating geometry have been chosen to synthesize a flat-top filter centered in the middle of the C-band ($\lambda_{\mathrm{ch}} = 1.55\,\mu\mathrm{m}$), designed on the Silicon Photonic platform. The silicon waveguides are simulated with thickness $h = 220\,\mathrm{nm}$, widths $w_1 = 570\,\mathrm{nm}$ and $w_2 = 450\,\mathrm{nm}$, separated by a gap $G = 200\,\mathrm{nm}$ and $L_{\mathrm{tot}} = 400\,\mu\mathrm{m}$ long; the grating structure has been simulated with pitch $\Lambda = 298\,\mathrm{nm}$, corrugation widths $\Delta w_1 = 50\,\mathrm{nm}$ and $\Delta w_2 = 30\,\mathrm{nm}$ and a hyperbolic tangent apodization profile $(f(x) = [1 + \tanh(\beta(1 - 2|x|^{\alpha}))]$ with $\alpha = 3,\ \beta = 3)$.



(a) (b) (c)

Figure 2: Phase match condition curves. **(a)** Single phase-match condition in passive unchirped device. **(b)** Effect of the waveguides temperature. **(c)** Effect of the waveguides temperature and multiple grating pitches.



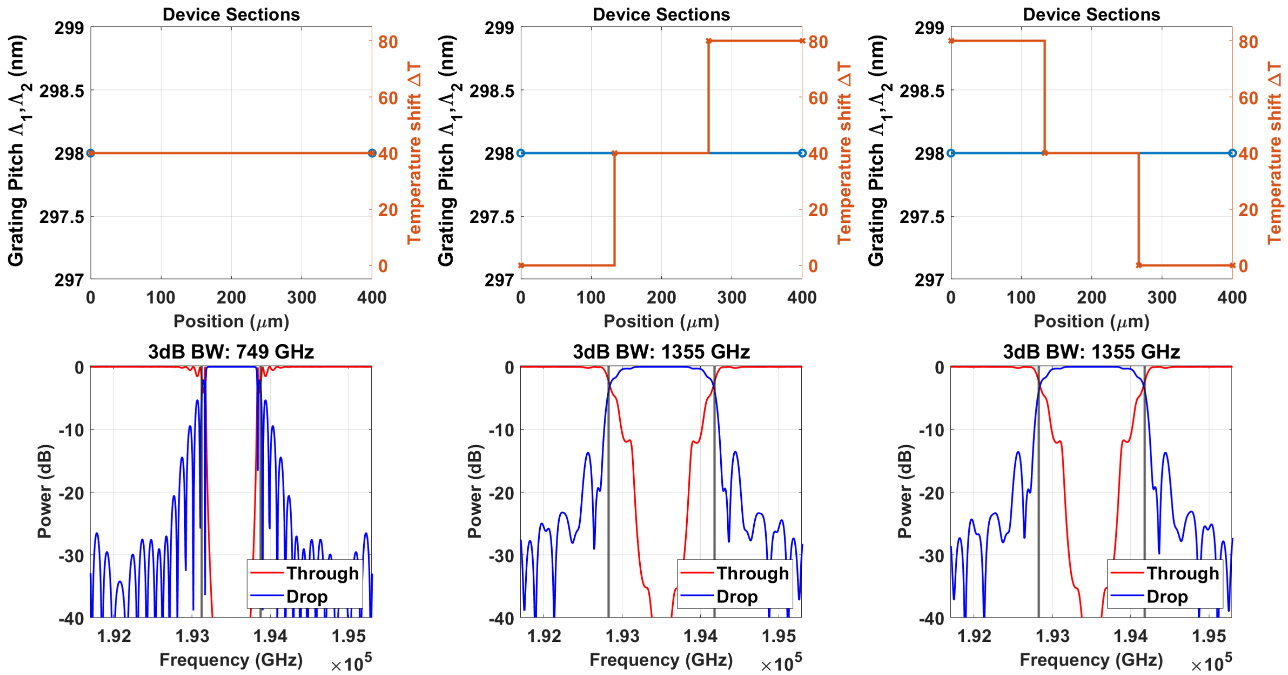
(a) (b) (c)

Figure 3: **(a)** Structure of the simulated spine heater. **(b)** Maximum temperature gradient achievable for the chosen heater geometry. **(c)** Example of piecewise thermal control along the heater spine.

3. TUNABILITY SCHEME

The control of the 3 dB bandwidth in GACDC can be obtained by modulating the phase-match condition, either through dynamic adjustment of the waveguide indices (thermo-optic or electro-optic effects) or the aforementioned pitch chirping Λ. The effect of both solutions is shown in Fig. 2: the drop wavelength can be adjusted, with pitch chirping representing the static solution to create wide-band or multi-channel behavior during design, and the thermal effect representing the dynamic reconfigurable adjustment. Although this effect primarily changes the channel wavelength, by controlling instead the overlap between multiple phase-match region the bandwidth can be modulated accordingly. In this analysis, the device has been simulated using established CMT methods,[12] assuming SOI implementation and thermal control: the thermo-optic coefficient for Silicon ($\frac{dn}{dT} \approx 1.86 \times 10^{-4}\,\mathrm{K}^{-1}$) has been considered constant, due to its small range of variation in the interval of interest.[13] The thermal behavior has instead been simulated through the COMSOL simulation suite, allowing evaluation of the gradient profiles and the heater response.

In our analysis, we have considered the IC layers available in the Silicon Photonic platform from Applied Nanotool (ANT).[14] The structure has been simulated considering a single microheater spine, which runs along the length of the device, with multiple side contact, allowing precise control of the voltages along the device Fig. 3a. The rib has been simulated with width $W = 3\,\mu\mathrm{m}$, contact spacing $\Delta L = 40\,\mu\mathrm{m}$, and ten contact points, acting as a parallel resistor circuit. The maximum achievable thermal shift has been evaluated by applying a voltage gradient across the contacts, assuming the operating limitations imposed by the maximum current density (safe operating value provided by ANT as $J = 50\,\mathrm{mA}/\mu\mathrm{m}^2$). The multiphysics simulations yielded waveguide temperatures up to $T = 100\,^\circ\mathrm{C}$ (Fig. 3a) while keeping the overall current density in the heater below the threshold (Fig. 3b): considering the ambient temperature, we obtain a $\Delta T = 80\,^\circ\mathrm{C}$ thermal offset that can be used to



(a) (b) (c)

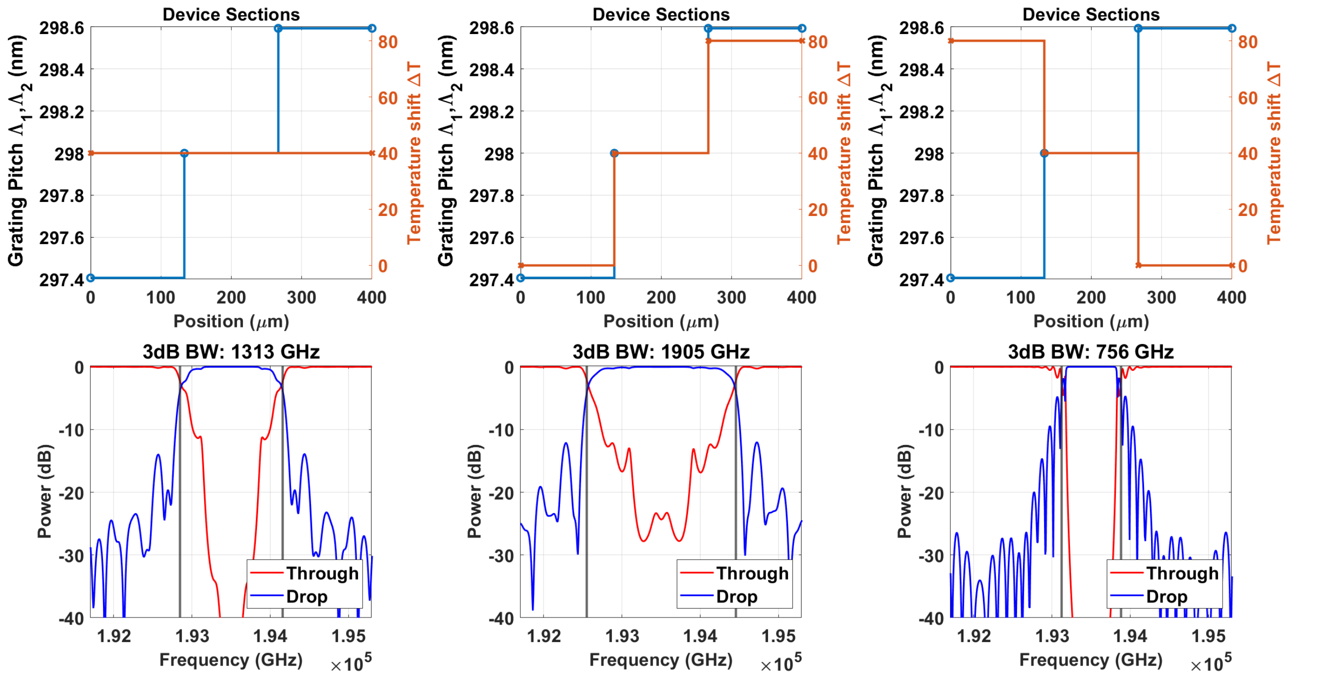
Figure 4: Drop bandwidth for the single pitch device: a) at default state b) under positive thermal chirp c) under negative thermal chirp.

calibrate and tune the device bandwidth. Moreover, Fig. 3c presents some of the piecewise step temperatures that can be obtained throughout the device, which will be used in the following section to explore the tunability range.

4. BANDWIDTH TUNABILITY RANGE

As introduced in the previous section, bandwidth control is obtained by leveraging phase-match region overlap. In single pitch devices (Fig. 4) we can see the limiting factor imposed by the temperature gradient. For the default state, a $\Delta T = 40\,°\mathrm{C}$ thermal offset is considered to maintain a consistent central channel,[15] leading to a reference bandwidth of $\mathrm{BW} = 749\,\mathrm{GHz}$ (Fig. 4a). By introducing the maximum thermal gradient, the device is shown to cover a bandwidth $\mathrm{BW} = 1355\,\mathrm{GHz}$, as shown in Fig. 4b-c: due to the single pitch, both positive and negative gradients lead to identical responses.
This limitation can be overcome introducing pitch-chirping, as shown in Fig. 5 where a device with three pitch regions is simulated ($\Lambda_1 = 297.4\,\mathrm{nm}$, $\Lambda_2 = 298\,\mathrm{nm}$, $\Lambda_3 = 298.6\,\mathrm{nm}$). The multiple phase-match conditions already increase the static bandwidth, with a passive value of $\mathrm{BW} = 1313\,\mathrm{GHz}$ (Fig. 5a).The second advantage of this design can be seen when a positive or negative thermal gradient is applied (Fig. 5b-c): while positive thermal gradient increases the bandwidth, as in the single-pitch case, up to $\mathrm{BW} = 1905\,\mathrm{GHz}$, now a negative gradient can be leveraged to decrease the bandwidth, down to the same reference bandwidth as in the passive case $\mathrm{BW} = 756\,\mathrm{GHz}$.
This showcases how pitch-chirping can extend the tunability range while maintaining the same lower bound present in the single-pitch device.
However, this technique cannot be scaled indefinitely, as any further increase would render the minimum achievable bandwidth larger than the original reference. Moreover, the separation of the phase-match region can introduce notches in the frequency response when the overlap starts to decease.

It is clear to see that pitch chirping can, at most, increase two-fold the bandwidth tunability ΔBW for a given thermal range: the chirped device can have static bandwidth equal to the maximum achievable bandwidth



(a) (b) (c)

Figure 5: Drop bandwidth for the pitch-chirped device: **(a)** default state, **(b)** under positive thermal chirp, **(c)** under negative thermal chirp.

of the original single-pitch device. The minimum bandwidth $\Delta\lambda_{\text{min}}$ corresponds to the complete overlap of the phase-match conditions obtained through a negative temperature gradient: any further decrease in the gradient can only lead to an increase in bandwidth, due to the inversion of the right and left phase-match conditions (similar to the symmetry experienced by the unchirped device in Fig. 4).
Similarly, the maximum bandwidth $\Delta\lambda_{\text{max}}$ that can be obtained through thermal gradient can at most correspond to twice the increment of the original (single-pitch) dynamic range. This limit also justifies the simplification into three main pitches and thermal regions in the proposed work, as additional thermal or pitch regions can only affect the smoothness and notches of the frequency response. The limiting factors for the tunability range are still dictated by the highest and lowest achievable phase match condition, which is intrinsically defined by the thermo-optical effect of the material.

5. CONCLUSIONS

The CMT model and COMSOL solver have been used to showcase index-gradient control to manipulate the drop channel bandwidth of GACDCs. The thermo-optic effect has been evaluated, highlighting its theoretical limitations in light of the material limitation and heater technology. After the evaluation of the bandwidth tunability boundaries in single-pitch devices, further enhancement methods have been investigated. Through pitch chirping, a two-fold increase in bandwidth tunability has been demonstrated while utilizing the same control mechanism with identical driving currents and covering the same original bandwidth of the unchirped solution.

6. ACKNOWLEDGMENTS

This contribution and the underlying research has been carried out thanks to the contribution of the Foundation Compagnia di San Paolo, under the initiative ”PoC Instrument (PoC – Proof of Concept)”.

REFERENCES

[1] Shekhar, S., Bogaerts, W., Chrostowski, L., Bowers, J. E., Hochberg, M., Soref, R., and Shastri, B. J., "Roadmapping the next generation of silicon photonics," *Nature Communications* **15**, 751 (Jan 2024).

[2] Akiyama, T., "Tutorial on silicon photonics applications," in [*2023 Optical Fiber Communications Conference and Exhibition (OFC)*], 1–56 (2023).

[3] Tunesi, L., Carena, A., Curri, V., and Bardella, P., "Thermally-controlled transparency in multi-ring cascaded filters," in [*Silicon Photonics XIX*], Reed, G. T. and Knights, A. P., eds., **12891**, 128910N, International Society for Optics and Photonics, SPIE (2024).

[4] Horst, F., Green, W. M., Assefa, S., Shank, S. M., Vlasov, Y. A., and Offrein, B. J., "Cascaded mach-zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-)multiplexing," *Opt. Express* **21**, 11652–11658 (5 2013).

[5] Minz, M. and Sonkar, R. K., "Design of a hybrid mode and wavelength division (de)multiplexer based on contra-directional grating assisted couplers on the SOI platform," *Appl. Opt.* **60**, 2640–2646 (3 2021).

[6] Tunesi, L., Khan, I., Masood, M. U., Ghillino, E., Curri, V., Carena, A., and Bardella, P., "Design and performance assessment of modular multi-band photonic-integrated wss," *Opt. Express* **31**, 36486–36502 (10 2023).

[7] Saha, N., Brunetti, G., Armenise, M. N., and Ciminelli, C., "Tunable narrow band add-drop filter design based on apodized long period waveguide grating assisted co-directional coupler," *Opt. Express* **30**, 28632–28646 (Aug 2022).

[8] Mu, D., Qiu, H., Jiang, J., Wang, X., Fu, Z., Wang, Y., Jiang, X., Yu, H., and Yang, J., "A four-channel dwdm tunable add/drop demultiplexer based on silicon waveguide bragg gratings," *IEEE Photonics Journal* **11**(1), 1–8 (2019).

[9] Shi, W., Wang, X., Lin, C., Yun, H., Liu, Y., Baehr-Jones, T., Hochberg, M., Jaeger, N. A. F., and Chrostowski, L., "Silicon photonic grating-assisted, contra-directional couplers," *Opt. Express* **21**, 3633–3650 (2 2013).

[10] Boroojerdi, M. T., Ménard, M., and Kirk, A. G., "Two-period contra-directional grating assisted coupler," *Opt. Express* **24**, 22865–22874 (10 2016).

[11] Shi, W., Greenberg, M., Wang, X., Wang, Y., Lin, C., Jaeger, N. A. F., and Chrostowski, L., "Single-band add-drop filters using anti-reflection, contra-directional couplers," in [*The 9th International Conference on Group IV Photonics (GFP)*], 21–23 (2012).

[12] Weber, J.-P., "Spectral characteristics of coupled-waveguide bragg-reflection tunable optical filter," *IEE Proceedings J (Optoelectronics)* **140**, 275–284(9) (10 1993).

[13] Glassbrenner, C. J. and Slack, G. A., "Thermal conductivity of silicon and germanium from 3°K to the melting point," *Phys. Rev.* **134**, A1058–A1069 (5 1964).

[14] Applied Nanotools, "NanoSOI MPW design rule." https://www.appliednt.com/nanosoi/sys/resources/rules/.

[15] Tunesi, L., Mahdian, M. A., Curri, V., Carena, A., Nikdast, M., and Bardella, P., "Thermal control scheme in contra-directional couplers for centered tunable bandwidths," in [*2023 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)*], 115–116 (2023).