Thermal Control Scheme in Contra-Directional Couplers for Centered Tunable Bandwidths

(Article begins on next page)

Thermal Control Scheme in Contra-Directional Couplers for Centered Tunable Bandwidths

Lorenzo Tunesi*, Mohammad Amin Mahdian†, Vittorio Curri*, Andrea Carena*, Mahdi Nikdast†, Paolo Bardella*
*Department of Electronics and Communications, Politecnico di Torino, Turin, Italy
†Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO, USA
Email: lorenzo.tunesi@polito.it, {amin.mahdian,mnikdast}@colostate.edu

***Abstract*—We present an analytical simulation and thermal control scheme for a pitch-chirped Contra-Directional Coupler, able to achieve a 5-nm bandwidth-tunability range for a C-band reference channel at 1.55 µm. The proposed structure showcases central wavelength consistency in different bandwidth configurations, as well as high thermal-crosstalk resiliency.**

***Index Terms*—Tunable bandwidth and filters, grating-assisted contra-directional couplers, chirped gratings, silicon photonics.**

I. Introduction

Grating-assisted Contra-Directional Couplers (CDCs) are promising candidates for integrated photonic filtering solutions due to their flexible design space, wide range of applications, and overall performances. CDCs are four-port devices capable of achieving wavelength-selective add-drop filtering, whose underlying operating principle is based on the wavelength-dependent reflection introduced by traditional Bragg gratings. In two-waveguide CDC configurations, the periodic (Λ) perturbations of the waveguide index allow selective coupling between the forward propagating mode of the first waveguide and the backward propagating mode of the second one, enabling add-drop operation. Also, by properly engineering the widths, gratings, and geometries of the two waveguides, complex coupling effects can be implemented [2]. Integration in the Silicon Photonic platform has been widely successful [1, 6, 5], with relatively high robustness with respect to manufacturing uncertainties. CDC structures can be designed to achieve flat-top wideband filtering; as such, they are ideal for Wavelength-Division Multiplexing (WDM) applications, where high roll-off, low crosstalk and channel flatness are relevant [7].

In this paper, we present novel techniques to enhance CDC bandwidth, together with a thermal control scheme to achieve active tuning of the device bandwidth while maintaining a constant channel central wavelength. Design and simulations have been carried out using analytical models well described in the literature and tested against experimental data [8].

II. CDC Structure Design and Optimization

The proposed structure is a C-band CDC filter with a central design frequency of λ=1551.3 nm and tunable bandwidth from $\Delta f_{min} \approx 0.7$ THz to $\Delta f_{max} \approx 1.35$ THz. The structure has been designed and simulated using the well-known Coupled-Mode Theory (CMT) model [10], which was used to implement a MATLAB solver capable of simulating arbitrary CDCs with varying parameters along the length. This allows us to use a relatively simple matrix formulation to handle more complex

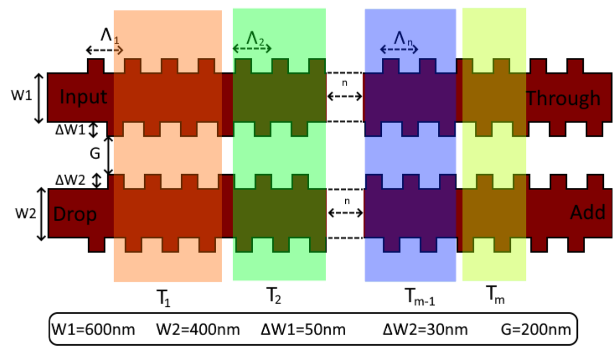
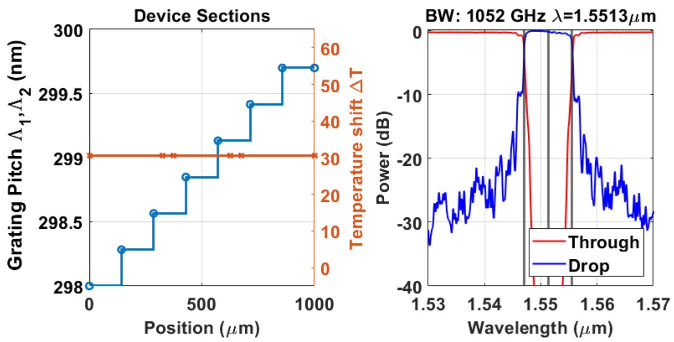


Fig. 1: CDC structure with arbitrary parameter chirp.

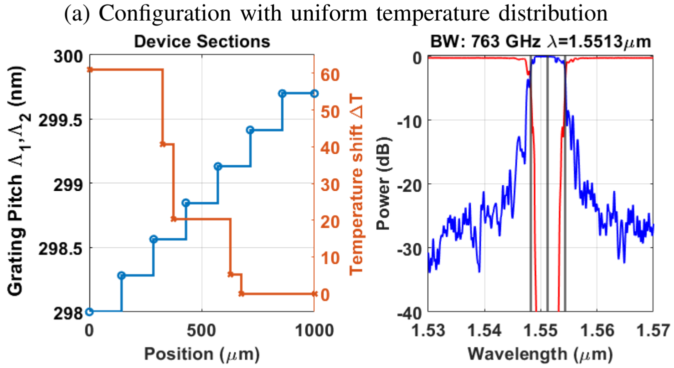
parameter variations, such as grating chirping, temperature gradients, as well as coupling apodization. As a result, we were able to design and simulate an arbitrary device with uneven regions, as depicted in Fig. 1. Moreover, different design strategies are considered to improve the performance of the device, such as using out-of-phase gratings to suppress backward reflections [9], apodization of the gratings for suppression of the sidelobes, and pitch chirping to increase the bandwidth [4]. The resulting structure's parameters are as follows: reflection coupling coefficients $\kappa_{11} = \kappa_{22} = 10\,\mathrm{cm}^{-1}$, coupling coefficient $\kappa_{12} = 200\,\mathrm{cm}^{-1}$, seven regions with pitches $\Lambda_{1-7} = [298, 298.3, 298.6, 298.8, 299.1, 299.4, 299.7]\mathrm{nm}$ over a total length $L = 1\,\mathrm{mm}$ with a hyperbolic tangent apodization ($\alpha = 3,\ \beta = 3$). The coupling coefficients have been chosen to fit the model with the performance of experimental devices in the cited literature, and represent reasonable values for both the contra-directional effect (κ_{12}), and the back-reflections of phase-shifted grating devices ($\kappa_{11},\ \kappa_{22}$).

III. Thermal Control and CDC Simulation

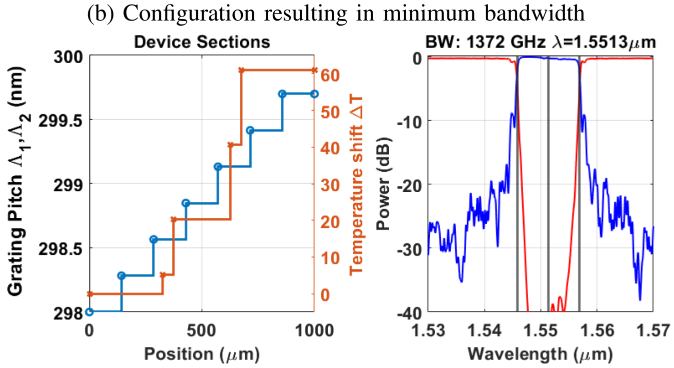
Having defined the main device parameters required by the model, the CDC can be simulated considering the effective indices of the two waveguides at the room temperature. To simulate the segmented heating scheme, the refractive index thermal dependency $\mathrm{d}n/\mathrm{d}T$ must be defined for both waveguides. Electro-thermal simulations were carried out using the RSoft Multiphysics tool, yielding $\mathrm{d}n_1/\mathrm{d}T \approx 1.008 \times 10^{-4}$ and $\mathrm{d}n_2/\mathrm{d}T \approx 0.843 \times 10^{-4}$ for the temperature-induced effective index shift at $\lambda = 1.55\,\mu\mathrm{m}$. In this analysis, the thermo-optic coefficient has been considered to be frequency independent and constant, due to the limited spectrum of interest (i.e., C band). Also, the maximum temperature shift considered is



(a) Configuration with uniform temperature distribution



(b) Configuration resulting in minimum bandwidth



(c) Configuration resulting in maximum bandwidth

Fig. 2: Thermal gradient over chirped regions (left) and the resulting frequency responses (right).

$\Delta T = 60\,°\text{C}$. Furthermore, in this analysis, symmetric heating is assumed; as such both waveguides are divided into the same regions and share the same temperature values in each section.

Fig. 2a showcases the first CDC configuration which represents the conventional case with no thermal gradient. The plot highlights the chirped regions as well as the relative temperature ΔT, considered with respect to the room temperature design at $T = 20\,°\text{C}$. As it is shown, all pitch regions are uniform in length (≈143 µm), while the thermal control is divided into three heating regions that are 325-μm, 250-μm, and 325-μm long, respectively. with 50 µm transition regions modeling the thermal crosstalk: by considering thermal roll-off instead of abrupt changes between the heating regions we can verify the tolerance and robustness of the control scheme.

The relative thermal bias of this configuration ($\Delta T = 30\,°\text{C}$) is applied to shift the frequency response and allow a fixed central wavelength for the increased and decreased bandwidth cases. Traditional thermal-control schemes introduce channel shifting when expanding the CDC bandwidth [3] while biasing the default case helps maintain a consistent channel in both the extended and reduced bandwidth cases. The idea behind the flexible bandwidth operation is to combine the benefits of both pitch chirping, together with temperature chirping or multielectrode control schemes. Considering the band-broadening effect of pitch chirping, which creates an effect similar to that of multiple cascaded CDCs with different drop wavelengths, the thermal shifts needed to realign part of the spectra are reduced, which in turn results in a more flexible device. The band tuning is achieved by shifting the lower-pitch or higher-pitch regions of the device, facilitating control over the left- and right-side of the transmission spectrum.

By maintaining a balance between the temperature increase in one region and its corresponding decrease in the other regions, the central frequency remains constant, allowing the bandwidth to be adjusted in either direction. As shown in Fig. 2b and Fig. 2c, the total bandwidth range can extend from 0.708 THz up to 1.352 THz, which represents a 52% tuning range (maximum to minimum) or a range of 70%–132% with respect to the constant temperature case. As shown by the temperature curves, even by considering thermal crosstalk through the center of the device, the resulting response does not exhibit notches or multichannel behavior, which highlights the robustness of the pitch-chirped CDC design.

IV. Conclusions

We have demonstrated the advantages of multi-region-based design and control in CDC structures to achieve flexible operation and consistent channel wavelength. The analytical solver coupled with physics thermal simulations allows for an accurate yet fast model to estimate the performance and design complex CDC add-drop filters.

References

[1] C. Alonso-Ramos et al. "Single-etch grating coupler for micrometric silicon rib waveguides". In: *Opt. Lett.* 36.14 (July 2011).

[2] M. T. Boroojerdi et al. "Two-period contra-directional grating assisted coupler". In: *Opt. Express* 24.20 (Oct. 2016).

[3] J. Cauchon et al. "Thermally chirped contra-directional couplers for residueless, bandwidth-tunable Bragg filters with fabrication error compensation". In: *Opt. Lett.* 46.3 (Feb. 2021).

[4] M. Hammood et al. "Broadband, silicon photonic, optical add–drop filters with 3 dB bandwidths up to 11 THz". In: *Opt. Lett.* 46.11 (June 2021).

[5] Amin Shafiee et al. "Inexact Silicon Photonics". In: *Photonics in Switching and Computing*. 2021.

[6] W. Shi et al. "Contradirectional couplers in silicon-on-insulator rib waveguides". In: *Opt. Lett.* 36.20 (Oct. 2011).

[7] Wei Shi et al. "Silicon CWDM demultiplexers using contra-directional couplers". In: *CLEO: 2013*. 2013.

[8] Wei Shi et al. "Silicon photonic grating-assisted, contra-directional couplers". In: *Opt. Express* 21.3 (Feb. 2013).

[9] Wei Shi et al. "Single-band add-drop filters using anti-reflection, contra-directional couplers". In: *The 9th International Conference on Group IV Photonics (GFP)*. 2012.

[10] J.-P. Weber. "Spectral characteristics of coupled-waveguide Bragg-reflection tunable optical filter". English. In: *IEE Proceedings J (Optoelectronics)* 140 (5 Oct. 1993).