7.5 μm wavelength fiber-chip grating couplers for Ge-rich SiGe photonics integrated circuits

Qiankun Liu, Joan Manel Ramirez, Vladyslav Vakarin, Daniel Benedikovic, Carlos Alonso-Ramos, Jacopo Frigerio, Andrea Ballabio, Giovanni Isella, Laurent Vivien, Delphine Marris-Morini

7.5 µm wavelength fiber-chip grating couplers for Ge-rich SiGe photonics integrated circuits

Q. Liu*[a], J. M. Ramírez[a], V. Vakarin[a], D. Benedikovic[a], C. Alonso-Ramos[a], J. Frigerio[b], A. Ballabio[b], G. Isella[b], L. Vivien[a], D. Marris-Morini[a]

[a]Centre de Nanosciences et de Nanotechnologies, Université Paris-Sud - Centre scientifique d'Orsay, Bât 220, Rue André Ampère, 91405 Orsay, France;

[b]L-NESS, Dipartimento di Fisica, Politecnico di Milano Polo di Como, Via Anzani 42 I 22100 Como, Italy

ABSTRACT

The mid infrared (MIR) region, which ranges from 2 µm to 20 µm, has attracted a lot of interest, particularly for novel applications in medical diagnosis, astronomy, chemical and biological sensing or security, to name a few. Most recently, Germanium-rich Silicon Germanium (Ge-rich SiGe) has emerged as a promising waveguide platform to realize complex mid-IR photonic integrated circuits. The Ge-rich SiGe graded buffer benefits from a wide transparency window, strong 3rd order nonlinearity, and the compatibility with mature large-scale fabrication processes, which in turn, paves the way for the development of mid-IR photonic devices that afford improved on-chip functionalities, altogether with compact footprints and cost-effective production. Albeit, low-loss waveguides and wideband Mach-Zehnder interferometers (MZIs) have been recently successfully demonstrated at mid-IR wavelengths, the coupling of light between external access ports, typically optical fibers, and integrated circuits remains challenging. Surface grating couplers provide technologically attractive scenario for light coupling, since they allow flexible placement on the chip, thereby enabling automatic testing of fabricated devices on a wafer-scale, preferred for large-volume developments. In this work, we report two designs for surface grating couplers implemented on the Ge-rich SiGe graded buffer. The grating couplers are designed for transverse electric (TE) and transverse magnetic (TM) polarizations, respectively, both operating at 7.5 µm wavelength. In particular, the TE-designed grating coupler with an inverse taper excitation arrangement yields a coupling efficiency of 6.3% (-12 dB), a 1-dB bandwidth of 300 nm, and reduced back-reflection less than 1%. Furthermore, the TM-designed grating coupler with a conventional taper injection stage predicts an improved coupling performance up to 11% (-9.6 dB), with a 1-dB bandwidth of 310 nm, and only 1% back-reflection. These results open up the way for the realization of complex and multifunctional photonics integrated circuits on Ge-rich SiGe platform with operation at mid-IR wavelengths.

Keywords: Mid-IR, Grating couplers, Silicon photonics, SiGe graded buffer

1. INTRODUCTION

The demonstration of compact, efficient and high output power cascade[1] and inter-band cascade[2] lasers in the mid-infrared range has paved the way for the development of integrated photonics devices with substantially extended operational wavelength. Mid-infrared (Mid-IR) integrated silicon photonics has become more and more attractive by societies, due to its potential in many applications, for example in mid-IR spectroscopy, free-space telecommunications or chemical and biological sensing among others[3]. Silicon photonics presents strong advantages for integrated photonics circuits due to its benefits from mature and high-volume fabrication to high performance, compact, low weight, low power consumption and cost-effective components for afore-mentioned applications. The most widely-used platform for silicon photonics is the silicon-on-insulator (SOI) whose operational wavelength range is limited by the buried oxide layer formed by silicon dioxide (SiO_2) up to about 3.6 µm due to the absorption. Many efforts have been done on other platforms in order to push the operational wavelength range beyond the oxide limit, such as silicon nitride, suspended silicon[4, 5]. Using this suspended silicon platforms, the operational wavelength range has been broadened up to 7.67 µm[5]. However, the operational wavelength is still limited under 8 µm due to the phonon absorption of silicon beyond 8 µm. Then other alternatives platforms, such as Germanium-on-insulator (Ge-on-SOI), Ge-on-Si[6] and Silicon-Germanium (SiGe) alloys[7-12] have been developed to take benefit from the wide transparency window of Ge up to 15 µm which cover almost the whole fingerprint region. Not only the wide transparency, but also high 3rd order non-linearity makes Ge an excellent material for the realization of mid-IR photonics circuits, especially for the sensing applications. Recent works on graded-index SiGe, include the design of flat anomalous dispersion SiGe waveguide[9] at mid-IR, or the demonstration of low-loss mid-IR waveguide[10] and ultra wideband Mach-Zehnder interferometer[11]. In the experimental demonstrations, coupling of light is usually done by butt-coupling using free space set-up. Surface grating couplers could provide attractive scenario comparing to the butt-coupling approach, since they allow flexible placement on the chip, and avoid the necessity from proper facet treatment. Many demonstrations have been already done on different platforms in near and early mid-IR wavelength range[13-18].

In this work, we report two designs for surface grating couplers implemented on the Ge-rich SiGe graded buffer. The grating couplers are designed for both transverse electric (TE) and transverse magnetic (TM) polarizations, respectively, operating at 7.5 µm wavelength. In particular, the TE-designed grating coupler with an inverse taper excitation arrangement yields a coupling efficiency of 6.3% (-12 dB), a 1-dB bandwidth of 300 nm, and reduced back-reflection less than 1%. Furthermore, the TM-designed grating coupler with a conventional taper injection stage predicts an improved coupling performance up to 11% (-9.6 dB), with a 1-dB bandwidth of 310 nm, and only 1% back-reflection. These results open up the way for the realization of complex and multifunctional photonics integrated circuits on Ge-rich SiGe platform with operation at mid-IR wavelengths.

2. DESIGN AND SIMULATIONS

2.1 Design of grating coupler in TE polarization

Grating couplers are designed for light coupling from optical fiber to a 6 µm-thick graded SiGe platform, where the SiGe alloys linearly change from pure Si to pure Ge. Low propagation loss waveguide have been recently demonstrated using this platform[10]. The gratings are designed at wavelength around 7.5 µm, first for TE polarization. The grating is designed to operate in a second diffraction order (k = -2) under a single-order radiation condition, substantially relaxing the aspect ratio requirements and facilitating device fabrication process. Figure 1 shows the grating coupler schematics. The grating period Λ is defined as the sum of the trench L_{Tr} and the tooth L_{To} lengths, with a duty cycle defined as $DC = L_{To}/\Lambda$. As shown in Figure 1, the device can be fabricated using a single-etch process. The optical fiber has a mode field diameter of ~13 µm[20], a grating width W_G of 18 µm provides an overlap higher than 99% between the lateral (x axis) profile of guided quasi-TE fundamental mode and the optical fiber mode.

The grating coupler diffraction is governed by the phase matching condition:

$$n_{uc} \sin(\theta_k) = n_B + \frac{k\lambda}{\Lambda} \tag{1}$$

where λ is the wavelength, k is the diffraction order, n_B is the effective index of the Bloch-Floquet mode in the grating region, θ_k is the radiation angle measured from the surface normal, and n_{uc} is the refractive index of the cladding upon the grating coupler. Taking into account that the effective index of the Bloch-Floquet mode is larger than the upper cladding, ($n_{air} = 1$) it can be deduced that only negative diffraction order can be radiated out of the grating coupler. As multiple diffraction beams propagating at different angles would result in poor coupling efficiency, the single diffraction beam is critical. The single-beam radiation condition has thus to be determined. Figure 2 reports the different radiation angles as a function of the grating period, for the different 3 first orders (k = -1, -2, -3), as calculated by the Eq. (1). For this calculation, the grating etch depth t_{etch} is set to 2 µm and the duty cycle DC is 0.4. The effective index of the Bloch-Floquet mode is calculated by 2D-Finite Difference Eigenmode (FDE) method, obtaining a value $n_B \sim 3.6$. Three regions can be distinguished in Figure 2, where only one order meets the radiation condition ensuring the single-beam radiation out of the coupler.

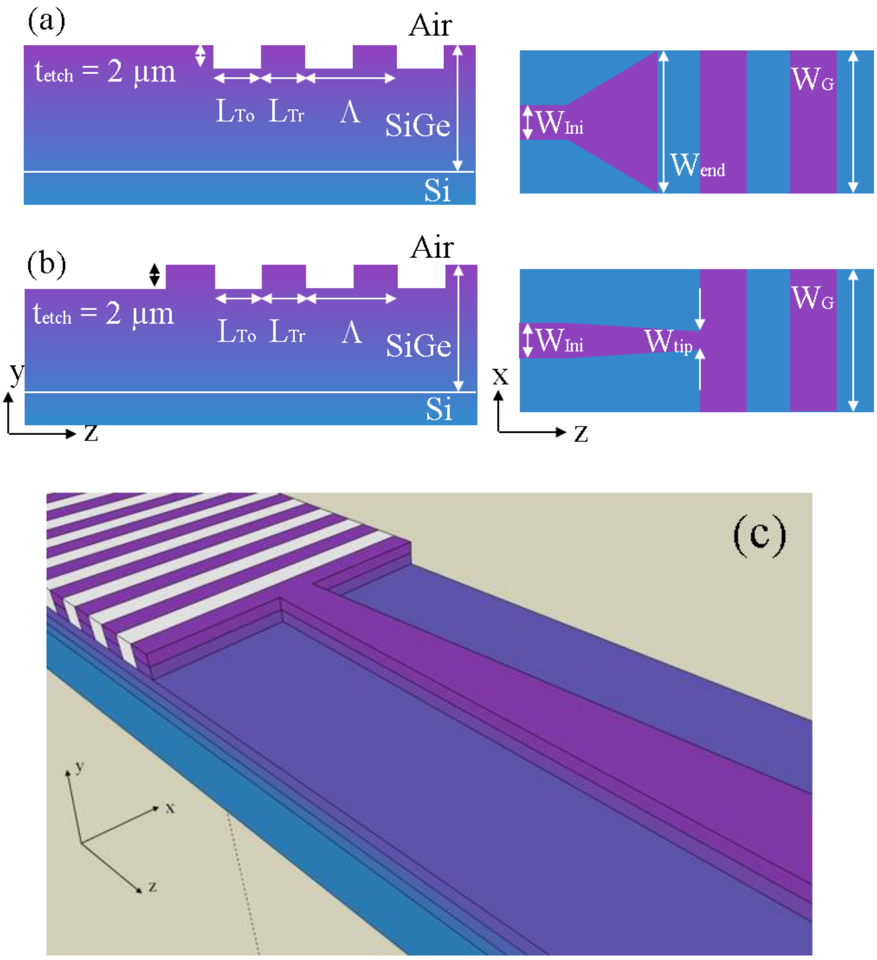

Figure 1. Grating coupler schematic: excitation stage with (a) a conventional taper and (b) an inverse taper; (c) 3D schema of grating coupler with an inverse taper.

The coupler performance in terms of reflectivity, directionality and coupling efficiency are then analyzed by using a 2D Finite-difference time-domain method. The results are plotted in Figure 2 (b) and (c) using 2 different taper designs to couple light from 4 µm-wide waveguide to the grating coupler. Compare to the conventional taper, the use of the inverse taper is to reduce the back-reflection at the interface of the single mode waveguide and the grating coupler, in order to increase the coupler performance. As the light is highly confined in the Ge-rich region of the SiGe waveguide where the refractive index is high, using a conventional taper would occur high reflectivity at the interface of waveguide and grating region. As shown in Figure 2, the coupler performance can be substantially increased by using an inverse taper excitation stage instead of a conventional taper. The designed grating coupler would require L_{Tr} = 2.75 µm and L_{To} = 1.75 µm (Λ = 4.5 µm) for k = -2 with a radiation angle of 14°. The inverse taper that connects the single mode waveguide (W_{ini} = 4 µm) and the grating coupler would require a taper tip W_{tip} = 1.8 µm, where the highest field overlap factor (86%) between the mode at the taper tip and the optimum excitation field could be obtained.

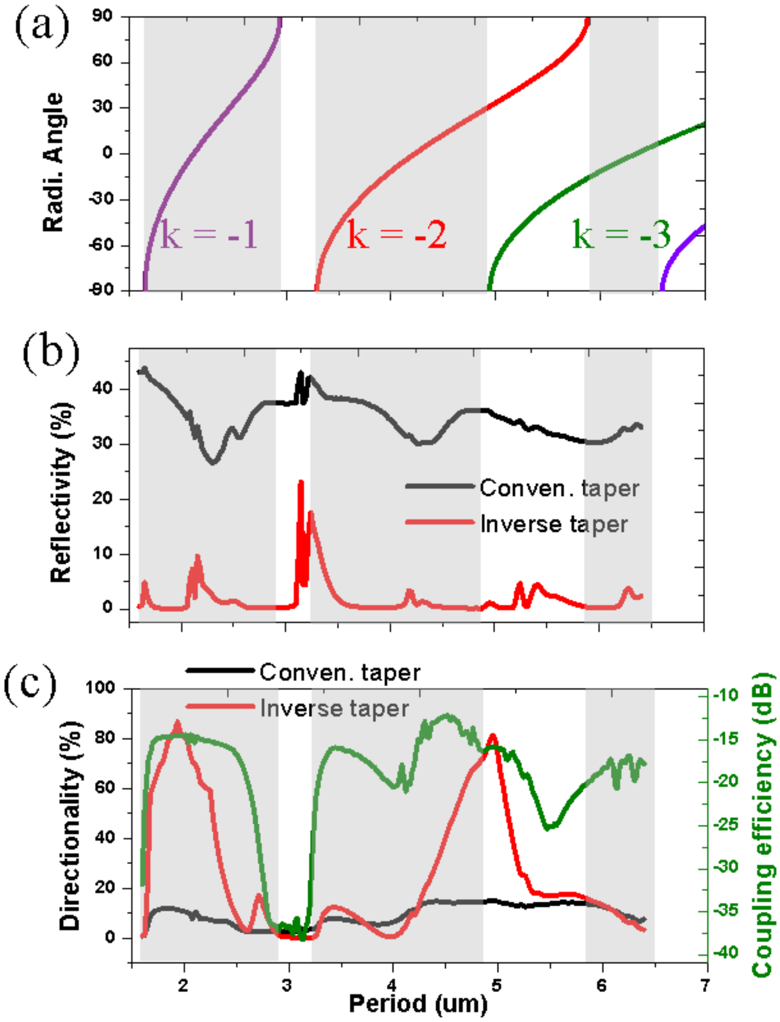

Figure 2. (a) Radiation angle in Eq. (1) as a function of grating period for different diffraction order; (b) Back-reflections and (c) coupling efficiency as a function of the grating period for a coupler with DC = 0.4

2.2 Design of grating coupler in TM polarization

For the design in TM polarization, the single-beam condition is also critical which as deduced from Eq. (1). The effective index of the Bloch-Floquet mode calculated by 2D-FDE method gives a value of $n_B \sim 3.64$. The designed grating coupler for transverse magnetic (TM) mode is excited with a conventional taper as shown in Figure 3. To optimize the coupler performance in TM mode, the 2D Finite-difference time-domain (2D-FDTD) method has also been performed. In this case the designed grating coupler for TM mode requires an etch depth of 1 µm instead of 2 µm etch depth previously defined for the TE polarization. Furthermore, the discontinuity between single mode waveguide and grating coupler is much smaller than for the TE mdoe. As a consequence, the back-reflection in TM polarization with a conventional taper is therefore negligible. The trench length L_{Tr} = 0.4 µm and tooth length L_{To} = 2.1 µm (Λ = 2.5 µm) are obtained for k = -1with a radiation angle of 46 °.

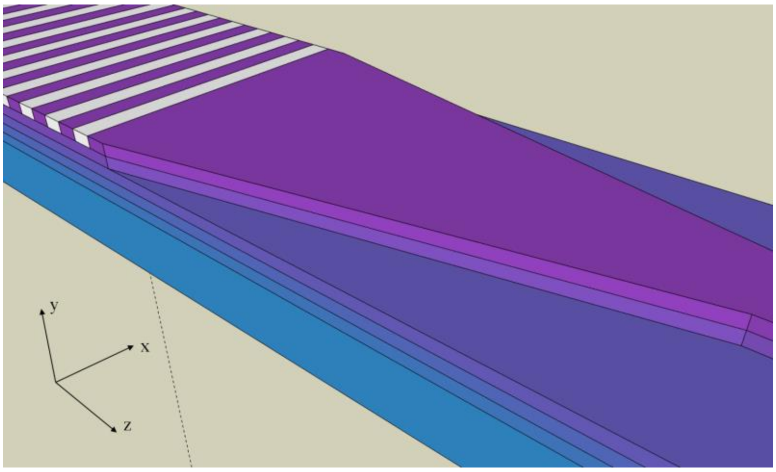

Figure 3. Schematic view the of grating coupler design for the TM polarization

2.3 Coupling efficiency

After designing the grating couplers for both TE and TM polarizations, the coupling efficiency can be evaluated using the following formula:

$$CE = \Gamma * \mathrm{T} \tag{2}$$

where T is the radiation power out of the grating and Γ is the overlap factor between the optical fiber mode and the grating. The top-radiated field escaping out of the grating can be calculated by using 2D-FDTD simulation, the overlap factor can be then calculated by an integration of this top-radiated field and the optical fiber mode over the surface of the grating coupler. The coupling efficiency of two designed grating couplers in TE and in TM polarization are shown in Figure 4. The coupling efficiency of the coupler designed for TE polarization is about -12 dB (6.3%) with a -1 dB bandwidth of 300 nm, and the coupler designed for TM polarization has a coupling efficiency about -9.6 dB (11%) with a -1 dB bandwidth of 310 nm.

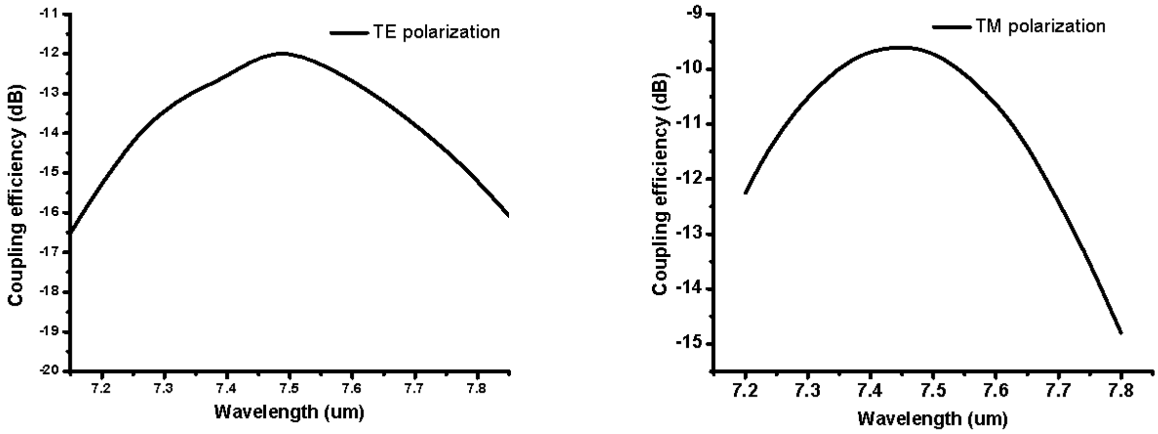

Figure 4. Coupling efficiency of the designed grating coupler for (a) TE polarization and (b) TM polarization

	Etch depth (µm)	$L_{Tr\ (\mu m)}$	$L_{To\ (\mu m)}$	Order	CE (dB)	Bandwidth (nm)
TE polarization	2	2.75	1.75	2	-12	300
TM polarization	1	0.4	2.1	1	-9.6	310

Table 5. Dimensions and performance of designed grating couplers

3. CONCLUSION

Two design of grating couplers based on SiGe graded waveguides operating at 7.5 µm for TE and TM polarization have been reported. The grating coupler designed for TE polarization has a coupling efficiency of 6.3% (-12dB), and the one designed for TM polarization has a coupling efficiency of 11% (-9.6dB). It could pave the way to large-volume fabrication on the SiGe graded platform, broadening the operational wavelength beyond the limit of silicon based platform.

ACKNOWLEGEMENTS

The authors acknowledge funding from European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (N°639107-INsPIRE). This work was partly supported by the French RENATECH network.

REFERENCES

[1] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, A. Y. Cho, "Quantum Cascade Laser", *Science*, vol. 264, Issue 5158, pp. 553-556 (1994)

[2] C. Borgentun, C. Frez, R. M. Briggs, M. Fradet, S. Forouhar, "Single-mode high-power interband cascade lasers for mid-infrared absorption spectroscopy", *Optics Express*, vol. 23, Issue 3, pp. 2446-2450 (2015)

[3] R. Soref, "Mid-infrared photonics in silicon and germanium", *Nature Photonics*, vol. 4, pp. 495-497 (2010)

[4] J. Soler Pennades, C. Alonso-Ramos, A. Z. Khokhar, M. Nedeljkovic, L. A. Boodhoo, A. Ortega-Monux, I. Molina-Fernandez, P. Cheben, G. Z. Mashanovich, "Suspended SOI waveguide with sub-wavelength grating cladding for mid-infrared", vol. 39, Issue 19, pp. 5661-5664 (2014)

[5] J. Soler Penades, A. Sanchez-Postigo, M. Nedeljkovic, A. Ortega-Monux, J. G. Wanguemert-Perez, Y. Xu, R. Halir, Z. Qu, A. Z. Khokhar, A. Osman, W. CAO, C. G. Littlejohns, P. Cheben, I. Molina-Fernandez, G. Z. Mashanovich, "Suspended silicon waveguides for long-wave infrared wavelengths", *Optics Letters*, vol. 43, Issue 4, pp. 795-798 (2018)

[6] C. Alonso-Ramos, M. Nedeljkovic, D. Benedikovic, J. Soler Penades, C. G. Littlejohns, A. Z. Khokhar, D, Perez-Galacho, L. Vivien, P. Cheben, G. Z. Mashanovich, "Germanium-on-silicon mid-infrared grating couplers with low-reflectivity inverse taper excitation", *Optics Letters*, vol. 41, pp. 4324-4327 (2016)

[7] V. Vakarin, P. Chaisakul, J. Frigerio, A. Ballabio, X. Le Roux, J. R. Coudevylle, D. Bouville, D. Perez-Galacho, L. Vivien, G. Isella, D. Marris-Morini, "Sharp bends and Mach-Zehnder interferometer based on Ge-rich-SiGe waveguides on SiGe graded buffer", *Optics Express*, vol. 23, pp. 30821-30826 (2015)

[8] P. Chaisakul, D. Marris-Morini, J. Frigerio, D. Chrastina, M. S. Rouifed, S. Cecchi, P. Crozat, G. Isella, L. Vivien, "Integrated germanium optical interconnects on silicon substrates", *Nature Photonics*, vol. 8, pp. 482-488 (2014)

[9] J. M. Ramirez, V. Vakarin, J. Frigerio, P. Chaisakul, D. Chrastina, X. Le Roux, A. Ballabio, L. Vivien, G. Isella, D. Marris-Morini, " Ge-rich graded-index Si1-xGex waveguides with broadband tight mode confinement and flat anomalous dispersion for nonlinear mid-infrared photonics", *Optics Express*, vol. 25, pp. 6561-6567 (2017)

[10] J. M. Ramirez, Q. Liu, V. Vakarin, J. Frigerio, A. Ballabio, X. Le Roux, D. Bouville, L. Vivien, G. Isella, D. Marris-Morini, “Graded SiGe waveguides with broadband low-loss propagation in the mid infrared”, *Optics Express*, vol. 26, pp. 870-877 (2018)
[11] V. Vakarin, J. M. Ramirez, J. Frigerio, A. Ballabio, X. Le Roux, Q. Liu, D. Bouville, L. Vivien, G. Isella, D. Marris-Morini, “Ultra-wideband Ge-rich silicon germanium integrated Mach Zehnder interferometer for mid infrared spectroscopy”, *Optics Letters,* vol. 42, Issue 17, pp. 3482-3485 (2017)
[12] J. M. Ramirez, V. Vakarin, C. Gilles, J. Frigerio, A. Ballabio, P. Chaisakul, X. Le Roux, C. Alonso-Ramos, G. Maisons, L. Vivien, M. Carras, G. Isella, D; Marris-Morini, “Low-loss Ge-rich Si0.2Ge0.8waveguides formid-infrared photonics”, *Optics Letters,* vol. 42, pp. 105-108 (2017)
[13] C. Alonso-Ramos, P. Cheben, A. Ortega-Moñux, J. H. Schmid, D.-X. Xu, I. Molina-Fernández, “Fiber-chip grating coupler based on interleaved trenches with directionality exceeding 95%”, *Optics Letters*, vol. 39, pp. 5351-5354 (2014)
[14] C. Alonso-Ramos, A. Ortega-Moñux, L. Zavargo-Peche, R. Halir, J. de Oliva-Rubio, I. Molina-Fernández, P. Cheben, D.-X. Xu, S. Janz, N. Kim, B. Lamontagne, “Single-etch grating coupler for micrometric silicon rib waveguides”, *Optics Letters*, vol. 36, pp. 2647-2649 (2011)
[15] D Benedikovic, C. Alonso-Ramos, P. Cheben, J. H. Schmid, S. Wang, D.-X. XU, J. Lapointe, S. Janz, R. Halir, A. Ortega-Moñux, J. G. Wanguemert-Perez, I. Molina-Fernández, J.-M. Fedeli, L. Vivien, M. Dado “High-directionality fiber-chip grating coupler with interleaved trenches and subwavelength index-matching structure”, *Optics Letters*, vol. 40, pp. 4190-4193 (2015)
[16] D. Benedikovic, P. Cheben, J. H. Schmid, D.-X. Xu, J. Lapointe, S. Wang, R. Halir, A. Ortega-Moñux, S. Janz, M. Dado, “High-efficiency single etch step apodized surface grating coupler using subwavelength structure”, *Laser & Photonics Review*, vol. 8, pp. 93-97 (2014)
[17] D. Benedikovic, C. Alonso-Ramos, P. Cheben, J. H. Schmid, S. Wang, R. Halir, A. Ortega-Moñux, D.-X. Xu, L. Vivien, J. Lapointe, S. Janz, M. Dado, “Single-etch subwavelength engineered fiber-chip grating couplers for 1,3 um datacom wavelength band”, *Optics Express*, vol. 24, pp. 12983-12904 (2016)
[18] S. Radosavljevic, B. Kuyken, G. Roelkens, “Efficient 5.2 µm wavelength fiber-to-chip grating couplers for the Ge-on-Si and Ge-on-SOI mid-infrared waveguide platform”, *Optics Express*, vol. 25, Issue 16, pp. 19034-19042 (2017)
[19] J. Kang, Z. Cheng, W. Zhou, T.-H. Xiao, K. Gopalakrisna, M. Takenaka, H. K. Tsang, K. Goda, “Focusing subwavelength grating coupler for mid-infrared suspended membrane germanium waveguides”, *Optics Letters*, vol. 42, Issue 11, pp. 2094-2097 (2017)
[20] SelenOptics, http://docs.wixstatic.com/ugd/541e1d_7129c860dab6400cb1ea9b8ce0281687.pdf