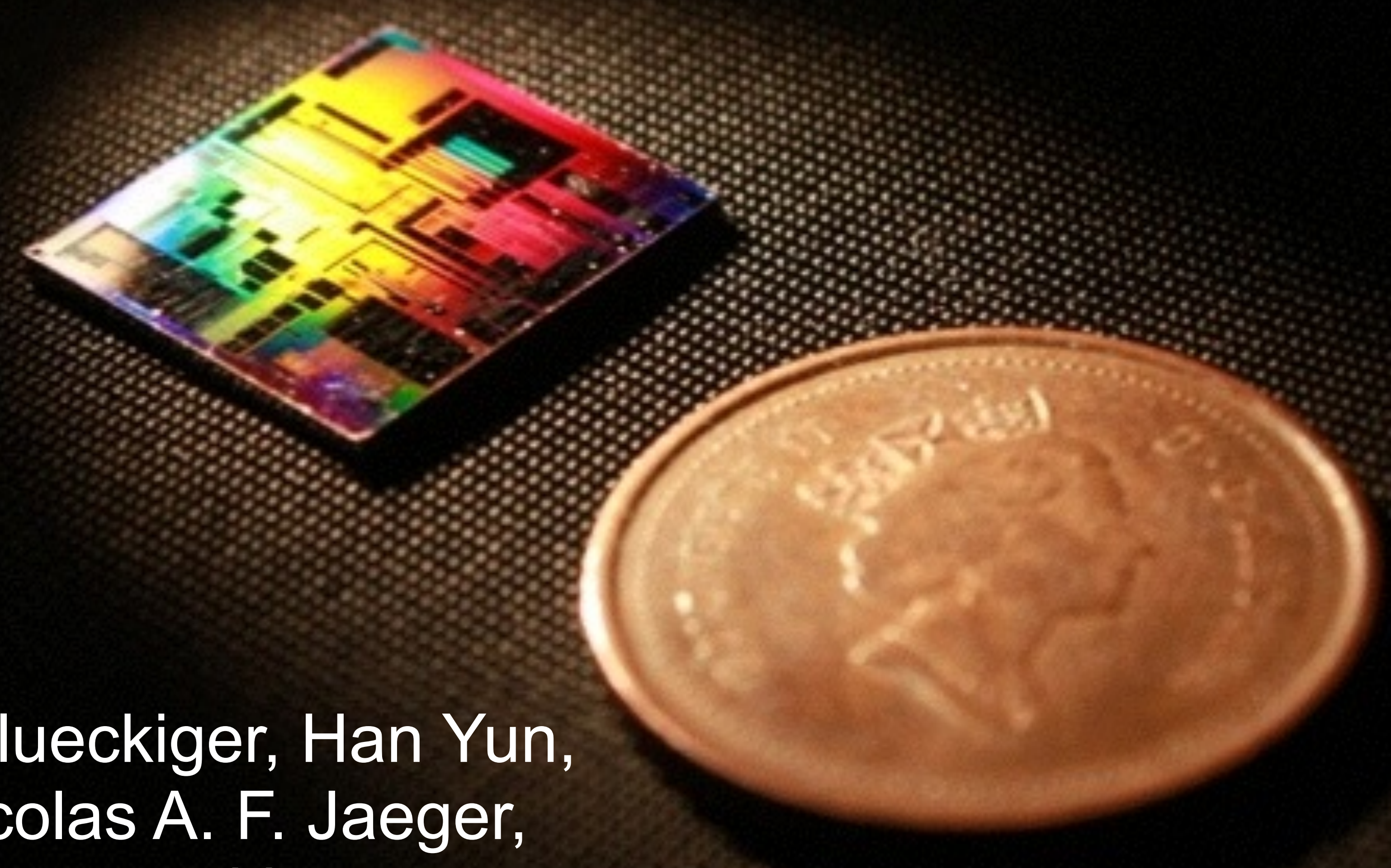
Focusing Sub-wavelength Grating Coupler

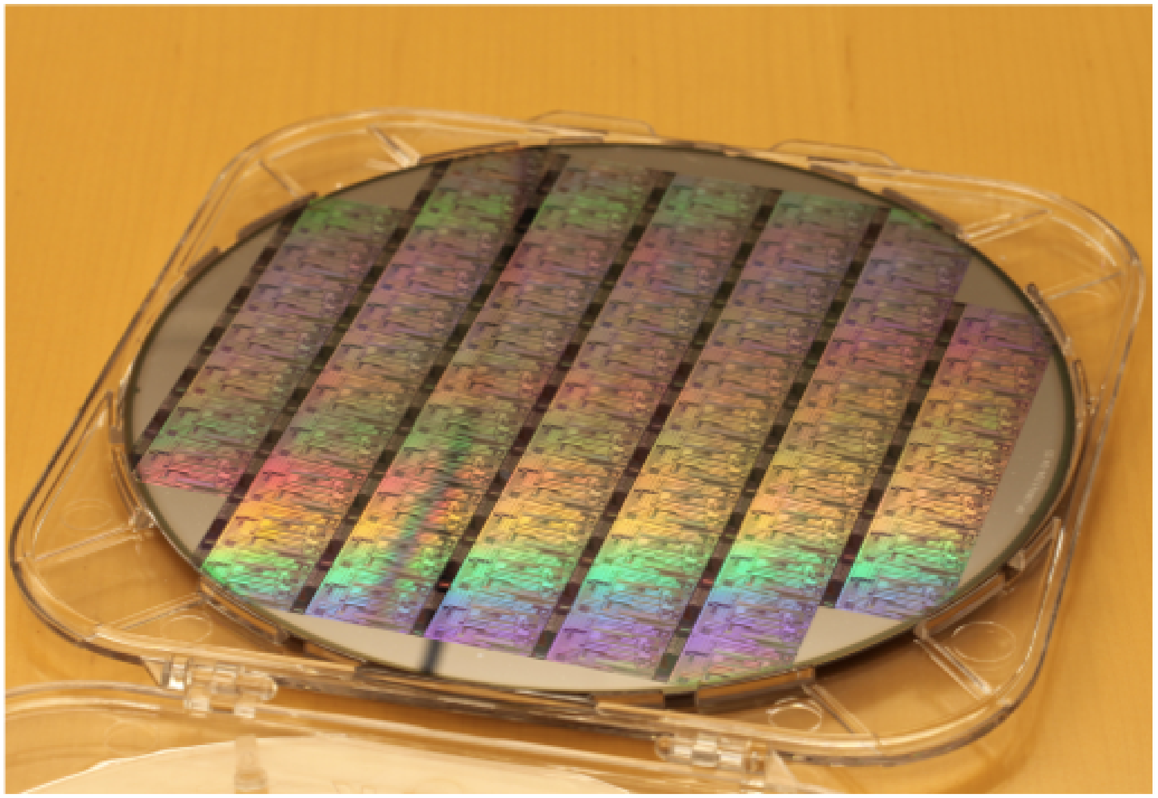


Yun Wang, Jonas Flueckiger, Han Yun,
Richard Bojko, Nicolas A. F. Jaeger,
Lukas Chrostowski

Overview

- Introduction
  - Silicon photonics and I/O devices;
  - Edge coupling vs. Surface coupling;
  - Shallow-etch vs. Full-etch;
- Focusing sub-wavelength grating coupler
  - Regular full-etch vs. sub-wavelength ;
  - Quasi-squares vs. grating lines;
  - Design methodology;
  - Simulations;
  - Setup and measurement;
- Future works;
- Summary;
- Acknowledgement

Silicon Photonics and I/O device



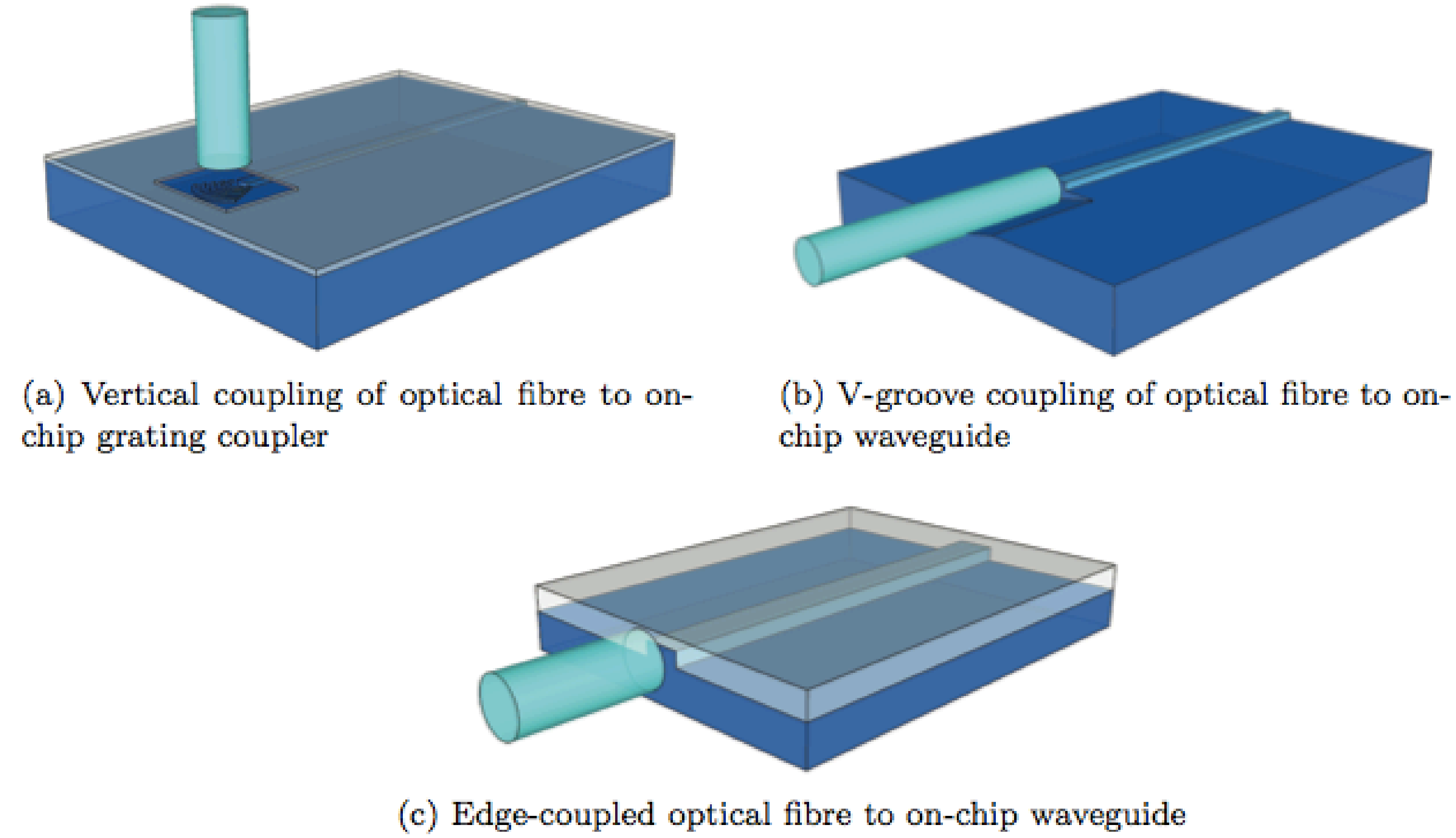


Fig.1 Photograph of 8” SOI wafer with various photonic components and circuits. [1]

Fig.2 Light coupling techniques [1]

- Silicon photonics: emerging technology leverages mature CMOS technology for operation of of light;
- High index contrast provides good modes confinement;
- Large mode-mismatches requires high-efficiency coupling techniques;

[1]. Lukas Chrostowski and Michael Hochberg, “Silicon Photonics Design”, Cambridge University Press, 2014

Edge coupling vs. surface coupling

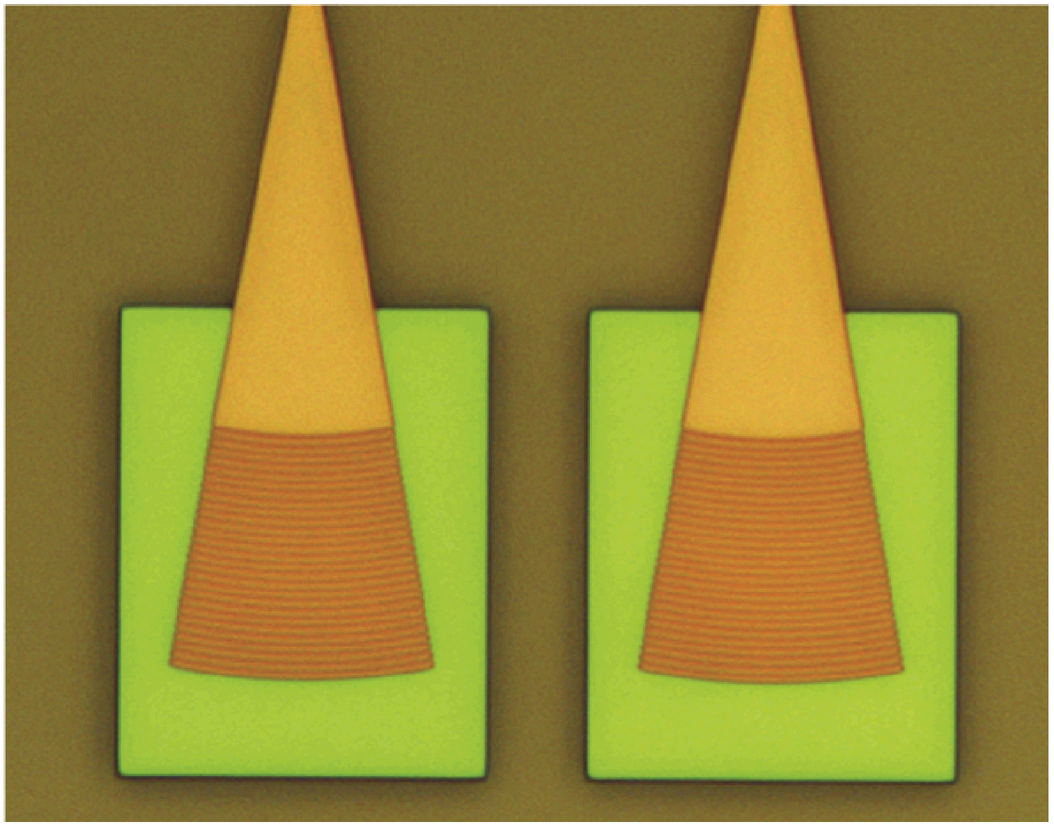


Fig.3 Optical micrograph of grating couplers [1]

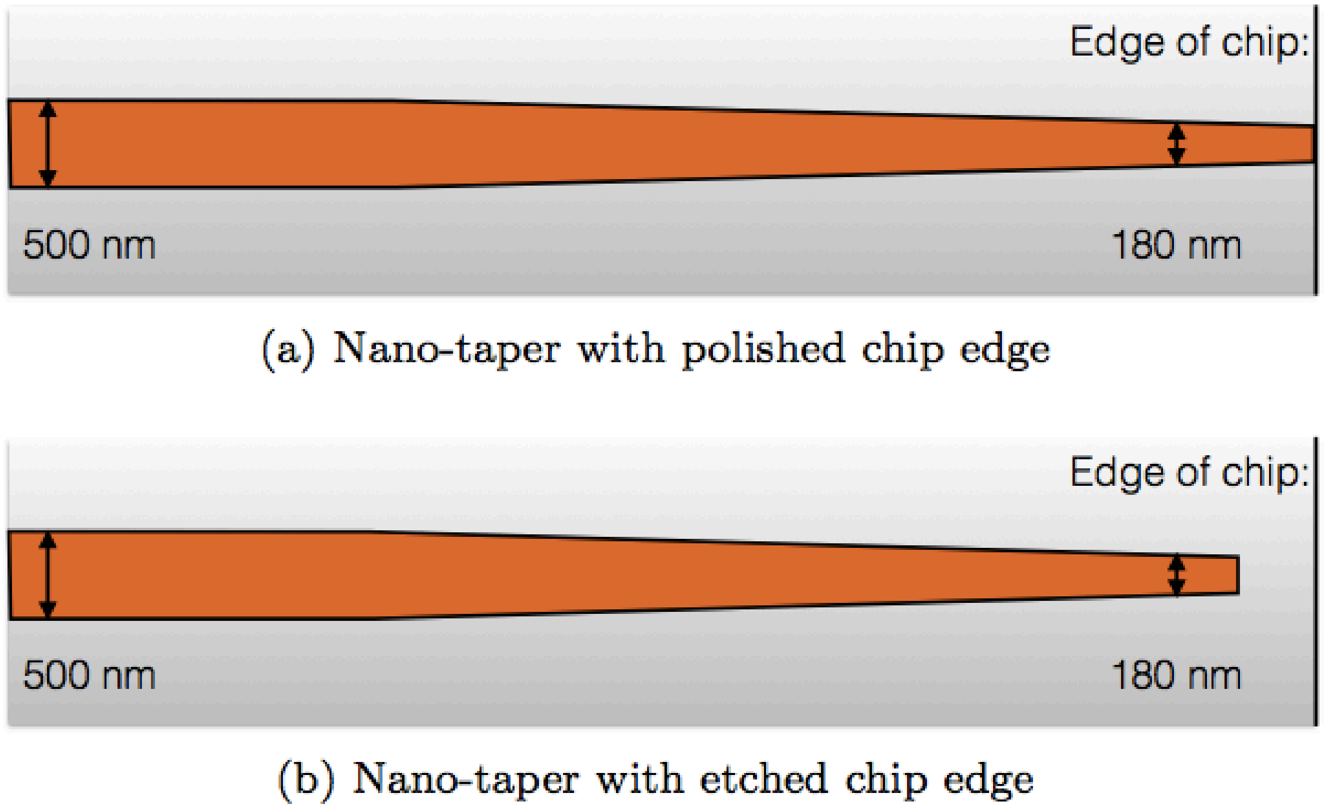


Fig.4 Illustration of nano-taper edge couplers [1]

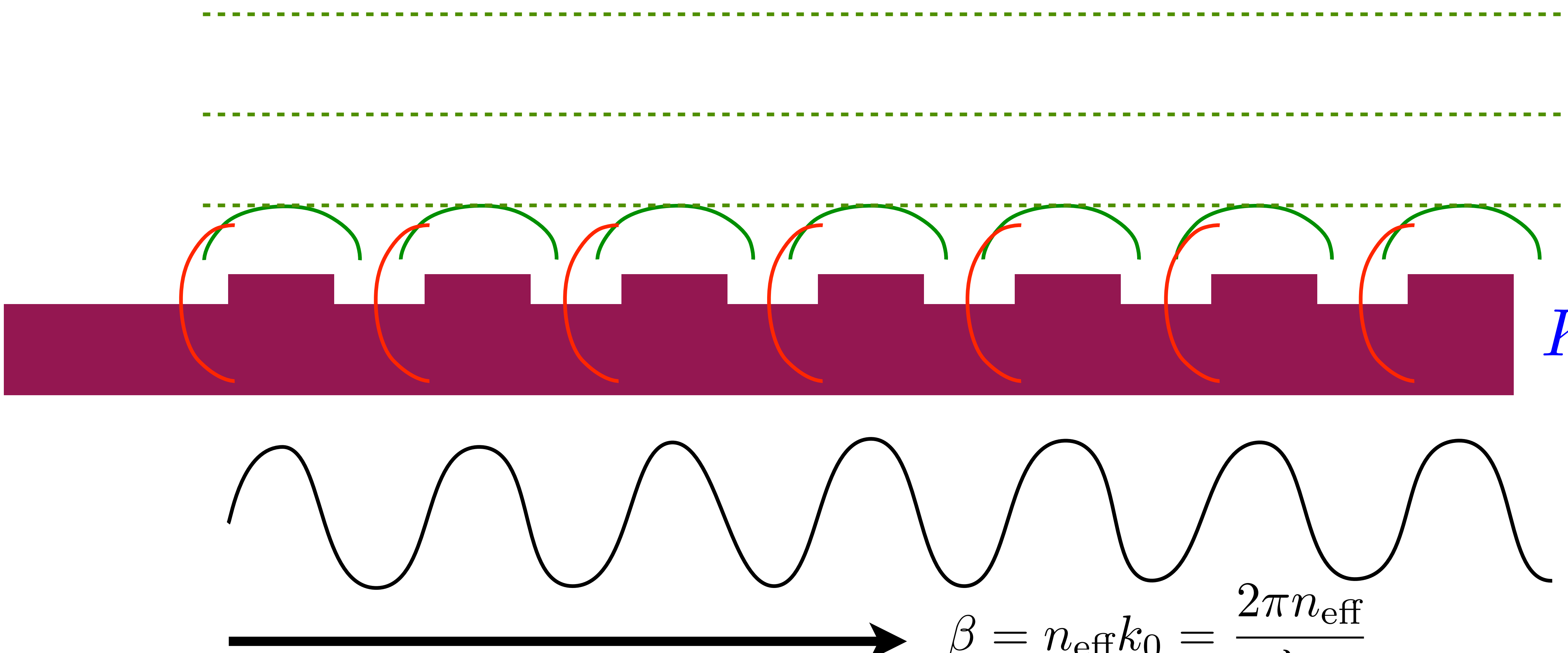
Pros of grating coupler based surface coupling method:

- Compact design; high-efficiency, easy alignment;
- Cost-effective: no-lensed fibre, no post process;
- Position flexibility for better architectural designs;
- Chip/wafer scale automated measurement;

[1]. Lukas Chrostowski and Michael Hochberg, "Silicon Photonics Design", Cambridge University Press, 2014

Grating Coupler – Operation

- Case 1 – Optical wavelength inside the grating matches its period, $\dfrac{\lambda_0}{n_{\text{eff}}} = \Lambda$



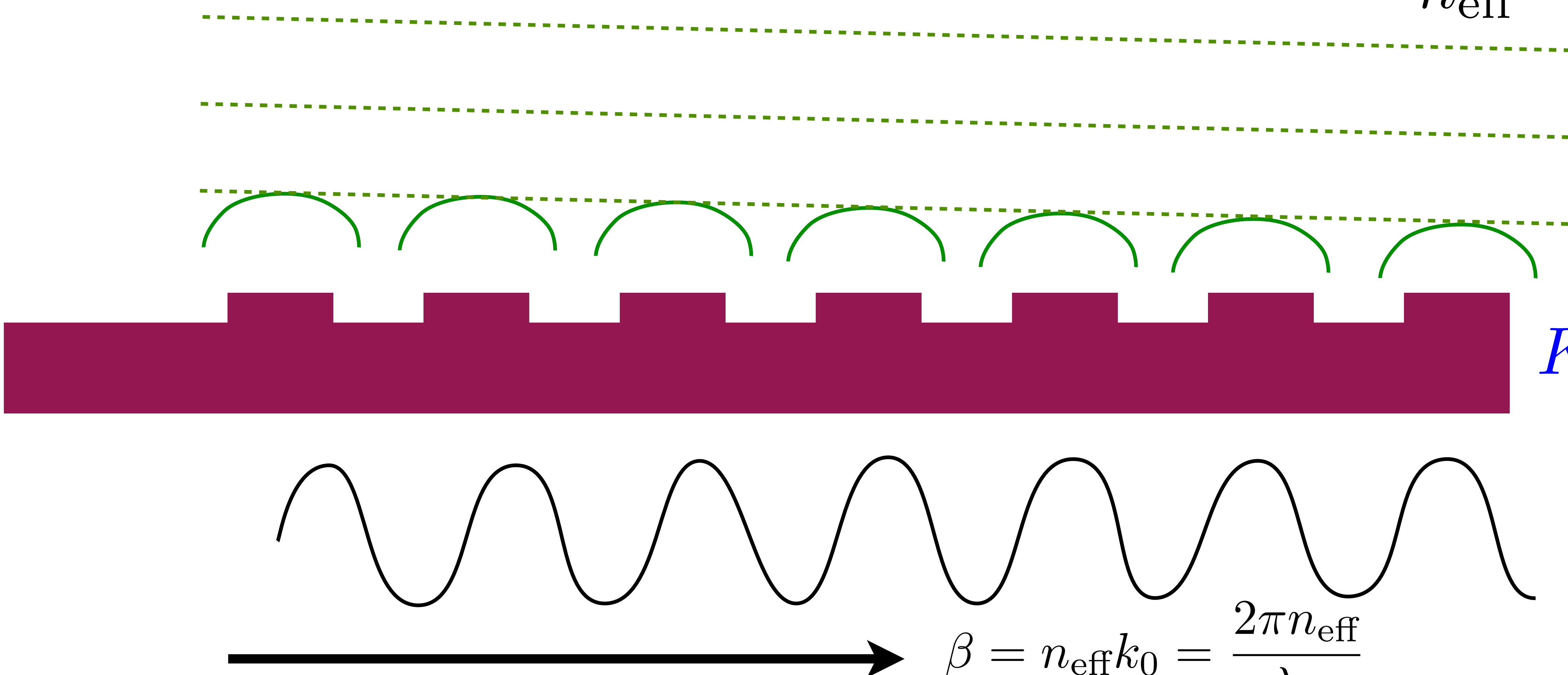
$$K = \frac{2\pi}{\Lambda}$$

$$\beta = n_{\text{eff}} k_0 = \frac{2\pi n_{\text{eff}}}{\lambda_0}$$

- Vertical output (1st diffraction order), plus back-reflection (from 2nd diffraction order)

Grating Coupler – Operation – Detuned

- Case 2 – Optical wavelength is smaller than the grating period, $\dfrac{\lambda_0}{n_{\text{eff}}} < \Lambda$

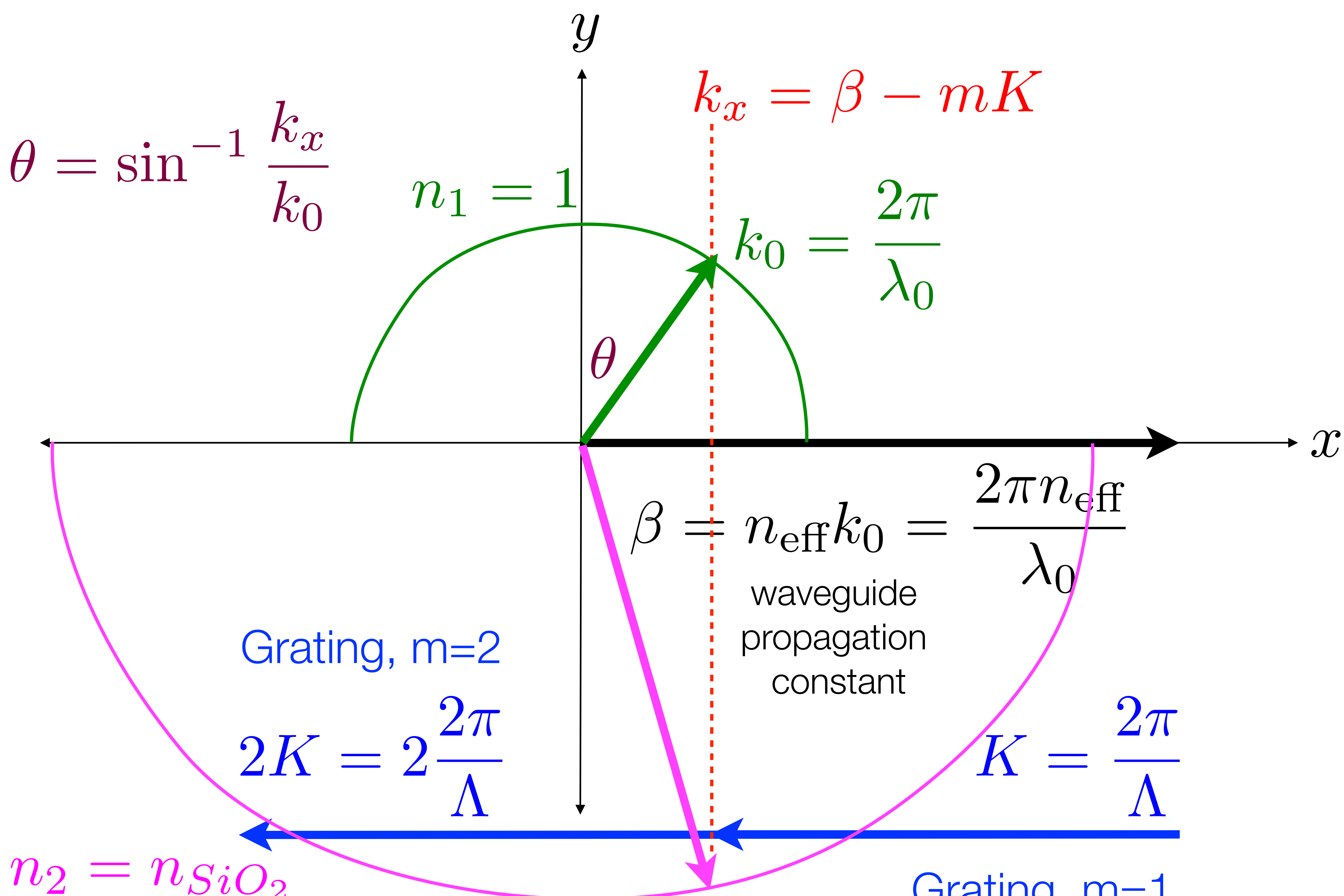


$$K = \frac{2\pi}{\Lambda}$$

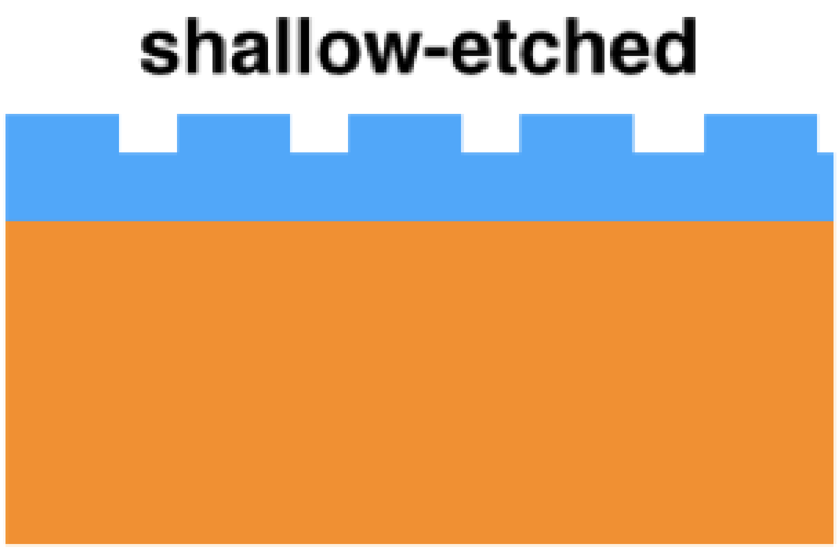
$$\beta = n_{\text{eff}} k_0 = \frac{2\pi n_{\text{eff}}}{\lambda_0}$$

- Vertical output at an angle, no 2^{nd} order back-reflection

Grating Coupler – Bragg Condition



Shallow-etch vs. fully-etched



(a) Shallow-etched grating coupler

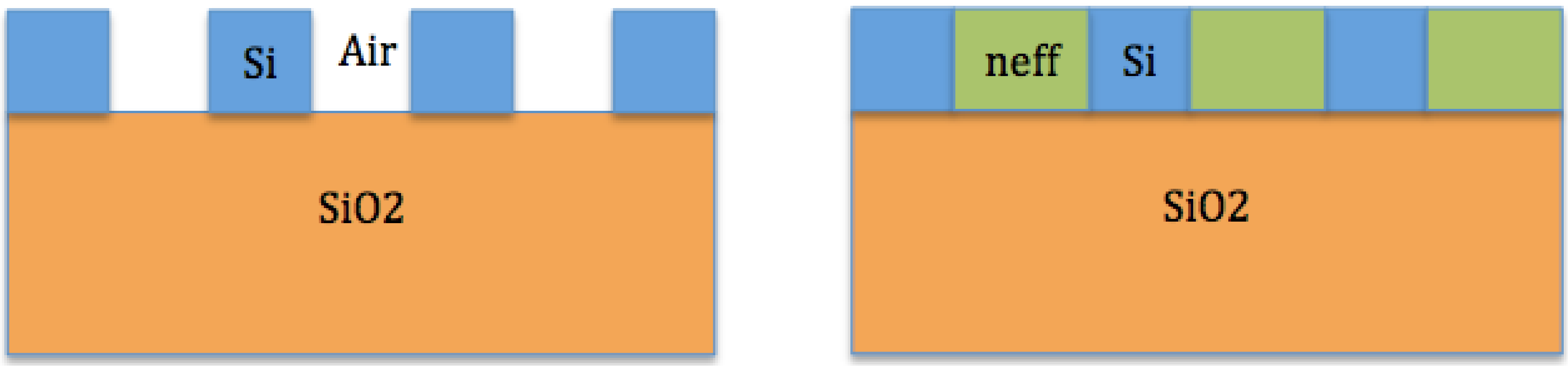
(b) Fully-etched grating coupler

Fig.5 Schematics of shallow-etched grating couplers and regular fully-etched grating coupler [2]

- Pros of fully-etched grating couplers:
  - Cost-effective (reduced etching steps and mask);
  - fast turn-around time for rapid prototyping;
- Cons of the fully-etched grating coupler:
  - Low coupling efficiency;
  - Large back reflection;
  - Small bandwidth;

[2]. Yun Wang, Xu Wang, Jonas Flueckiger, Han Yun, Wei Shi, Richard Bojko, Nicolas A.F. Jaeger, and Lukas Chrostowski , "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonics circuits", OE, 2014

Regular full-etch vs. sub-wavelength



(a) Regular fully-etched grating coupler

(b) Sub-wavelength fully-etched grating coupler

Fig.6 Schematics of regular fully-etched grating couplers and sub-wavelength fully-etched grating coupler.

Regular Fully-etch Grating Couplers:

- Fresnel reflection at the Si/Air interfaces cause large reflections;
- Fabry-perot cavity between I/O gratings leads to undesired ripples;
- Reflection loss also leads to poor coupling efficiency;
- Strong scattering cause narrow bandwidth;

Sub-wavelength grating couplers:

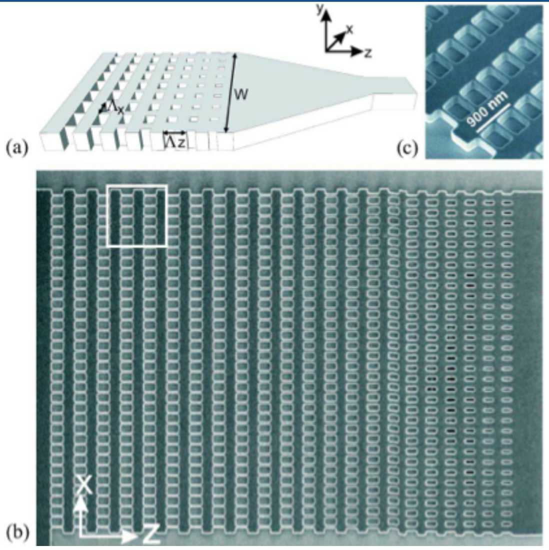
- Effective index areas are formed between the major gratings;
- Reduced index contrast decreases the reflection,;
- Better coupling efficient and broader bandwidth;

State-of-the-art SWG GC

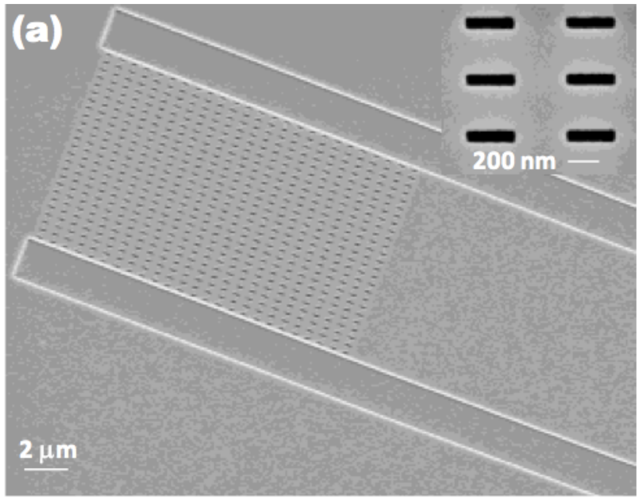
Ref.	Wl.(nm)	Pl.	IL	Bandwidth	Ripples	Wafer and design info.
[1]	1550	TM	3.7 dB	3-dB 60nm 1-dB:38nm	~ 0.15 dB	260nm Si; 2um BOX Straight grating+ adiabatic taper
[2]	1550	TE	2.29 dB	3-dB:60nm 1-dB:32nm	~ 0.3 dB	250 nm Si; 1um BOX Straight grating+ 500um taper
[3]	1510	TM	3 dB	3-dB: 50nm	NA	340nm Si, 2um BOX Focusing grating
[4]	1550	TE	1.74	3-dB: 60nm	NA	250nm Si; 1um BOX Straight grating + 500um taper
[5]	1550	TE	4.7 dB	1dB >100 nm	~0.3 dB	220nm Si, 3um BOX Focusing grating
This work	1550	TE	4.05	3-dB:52nm 1-dB: 36nm	~0.2 dB	220nm Si, 3um BOX Focusing grating
	1550	TM	3.74	3-dB:82nm 1-dB: 47nm	~0.1dB	220nm Si, 3um BOX Focusing grating

[1]. R.Halir, et.al, “Continuously apodized fiber-to-chip surface grating coupler with refractive index engineered sub wavelength structure”,OL, 2010;
[2].Xiaochuan Xu, et.al, “CMOS compatible Subwavelength Grating Couplers For Silicon Integrated Photonics”, IEEE, IPC, 2012;
[3] Zhenzhou Chen, et.al, “Apodized focusing subwavelength grating couplers for suspended membrane waveguide”, APL, 2012;
[4] Yunhong Ding, et.al, “ultrahigh efficiency apodized grating coupler using fully etched photonic crystal”, OL, 2013;
[5] Qiuhang Zhong, et.al, “Focusing-curved subwavelength grating couplers for ultra-broadband silicon photonics optical interface, OE, 2014;

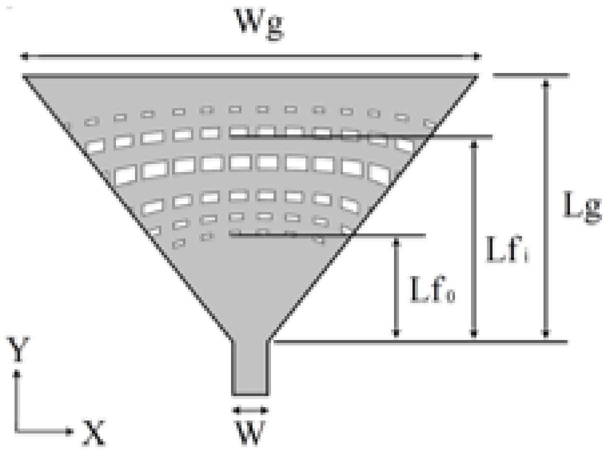
State-of-the-art SWG GC



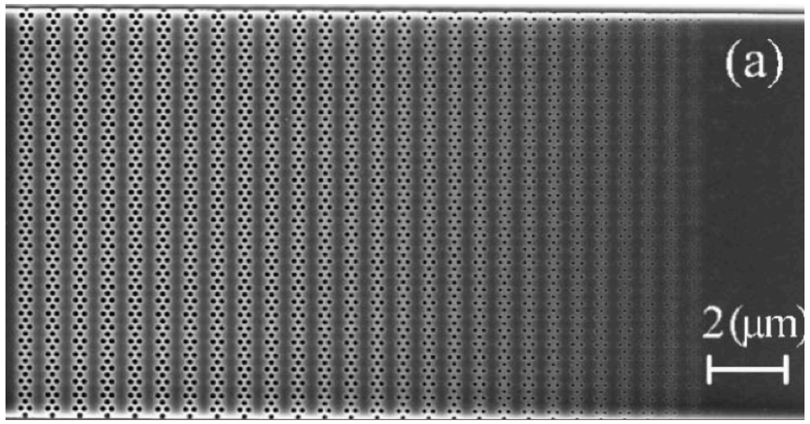
[1] TM SWG fully-etched GC from R. Halir



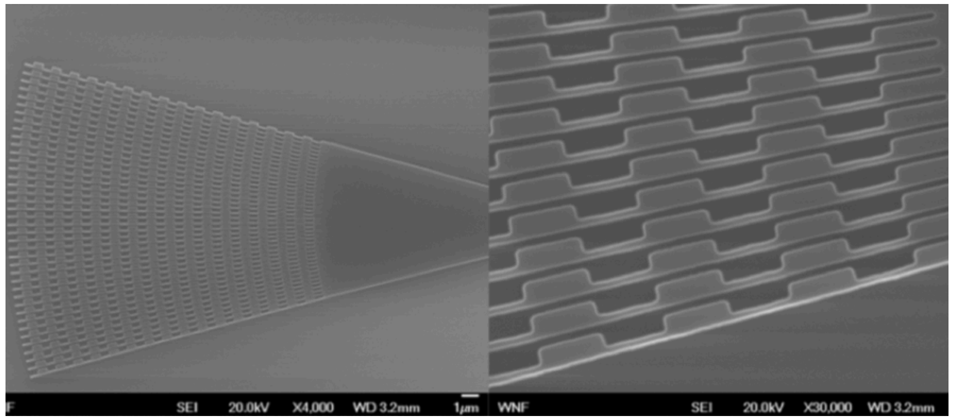
[2] TESWG fully-etched GC from Xiaochuan Xu



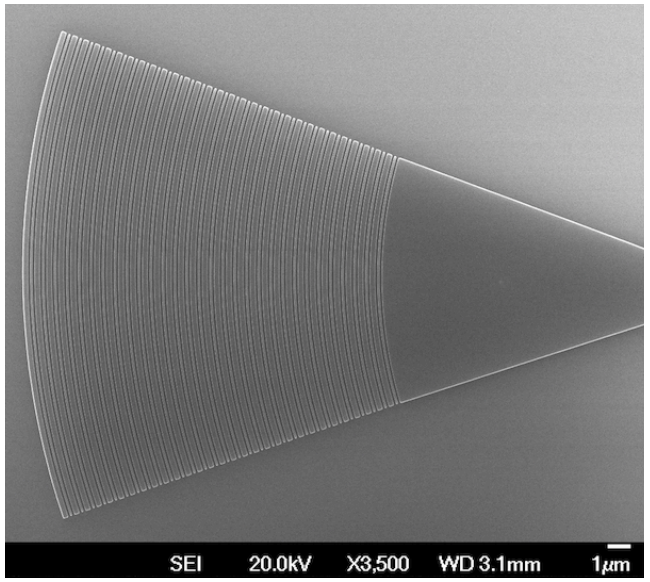
[3] TM SWG fully-etched GC from Zhenzhou Chen



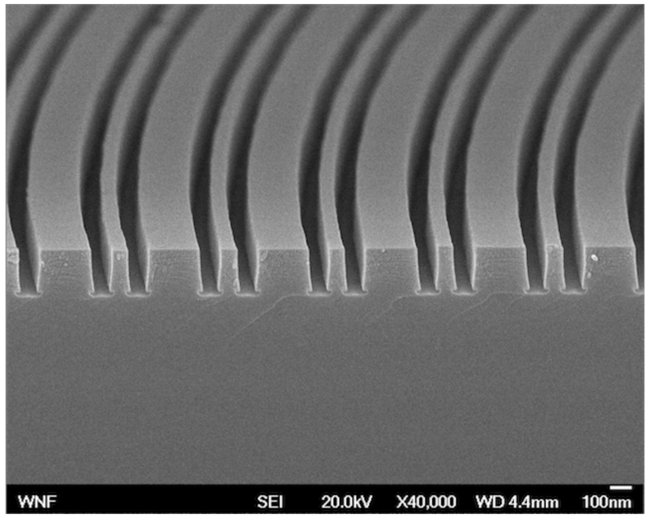
[4] TE SWG fully-etched GC from R. Yunhong Ding



[5] TE SWG fully-etched GC from Qiuhang Zhong



(a)



(b)

Fig.8 SEMs for this work (a),(b)

[1]. R.Halir, et.al, “Continuously apodized fiber-to-chip surface grating coupler with refractive index engineered sub wavelength structure”,OL, 2010;
[2].Xiaochuan Xu, et.al, “CMOS compatible Subwavelength Grating Couplers For Silicon Integrated Photonics”, IEEE, IPC, 2012;
[3] Zhenzhou Chen, et.al, “Apodized focusing subwavelength grating couplers for suspended membrane waveguide”, APL, 2012;
[4] Yunhong Ding, et.al, “ultrahigh efficiency apodized grating coupler using fully etched photonic crystal”, OL, 2013;
[5] Qiuhang Zhong, et.al, “Focusing-curved subwavelength grating couplers for ultra-broadband silicon photonics optical interface, OE, 2014;

Different sub-wavelength structures

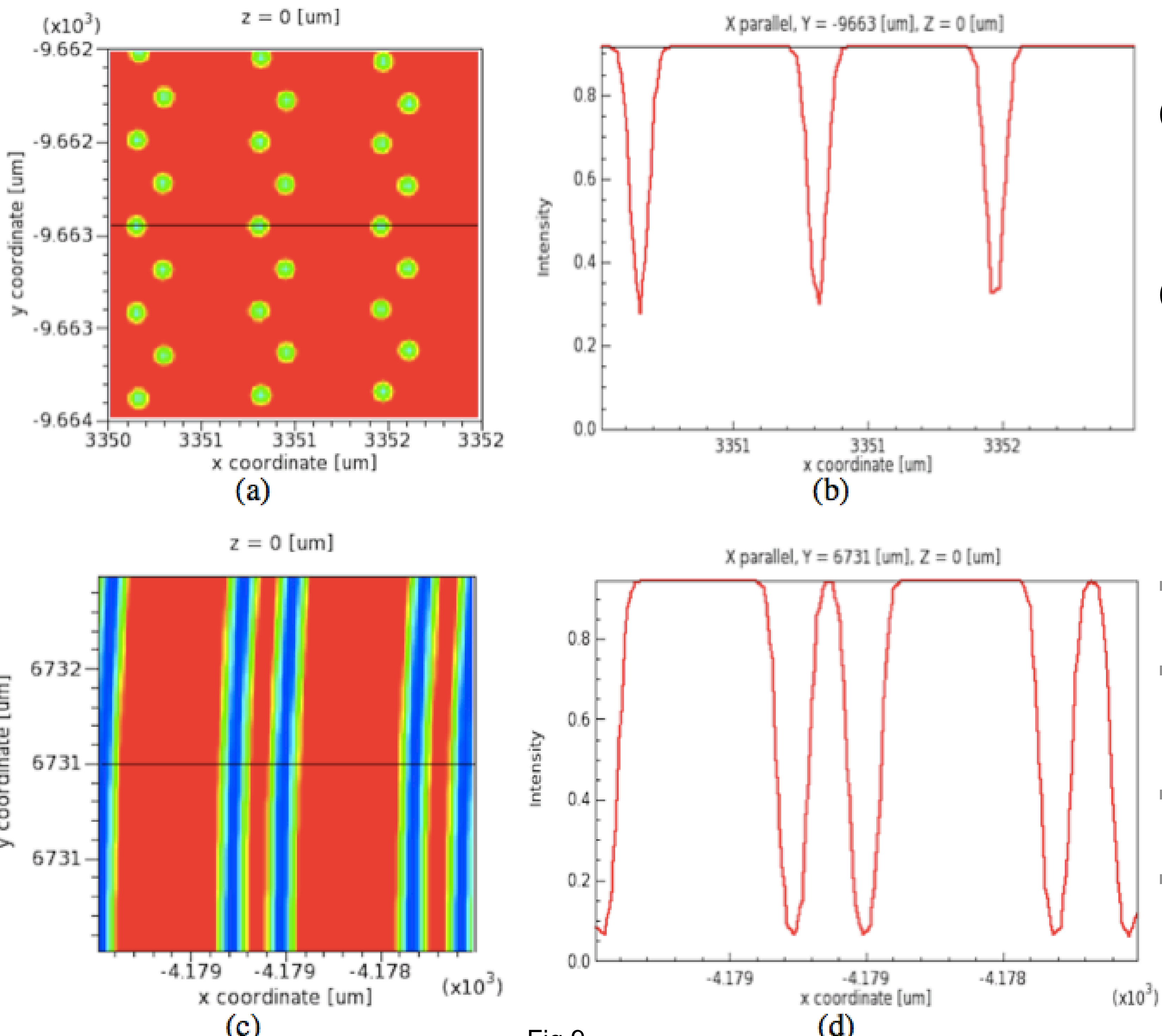


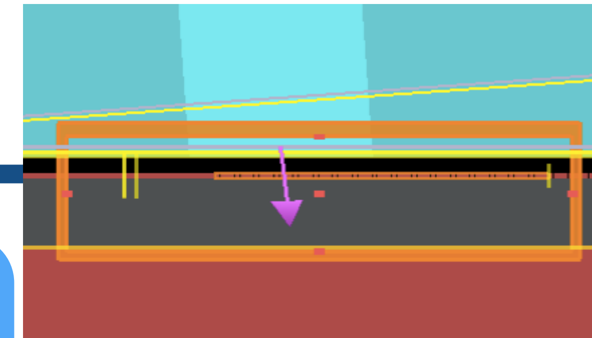
Fig.9

(a) &(c)2D energy distribution of sub-wavelength grating couplers formed by quasi-squares and sub-wavelength grating lines;

(b) &(d) energy distribution along the 1-D cutline across the 2-D simulation of sub-wavelength grating coupler formed by quasi-squares;

- Different sub-wavelength structures to obtain effective index region;
- Quasi-squares are more challenging for fabrication, low repeatability and poor sustainability;
- Sub-wavelength grating lines are easier to achieve with better accuracy;
- Grating lines are straightforward to convert to compact designs with focusing lines;

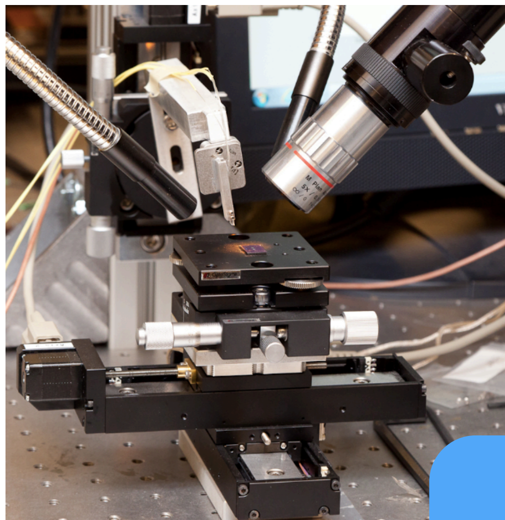
Design methodology

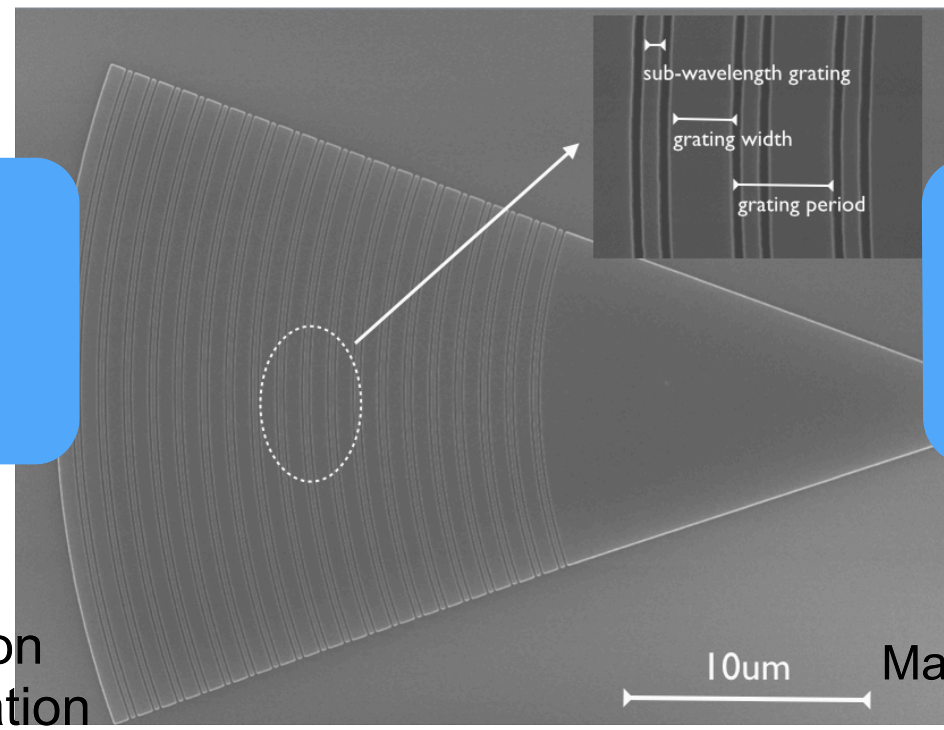


2D FDTD simulation for parameter optimization using Lumerical's FDTD Solutions

Model Verification

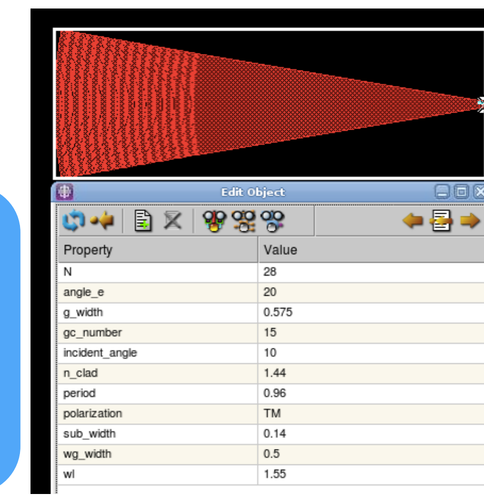
Design Parameters





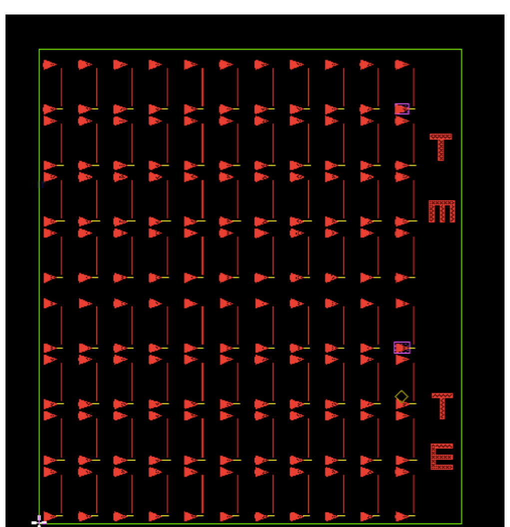
Fabrication & Measurement

Mentor Graphics's Pyxis Building Script Based Layout model



Submission for fabrication

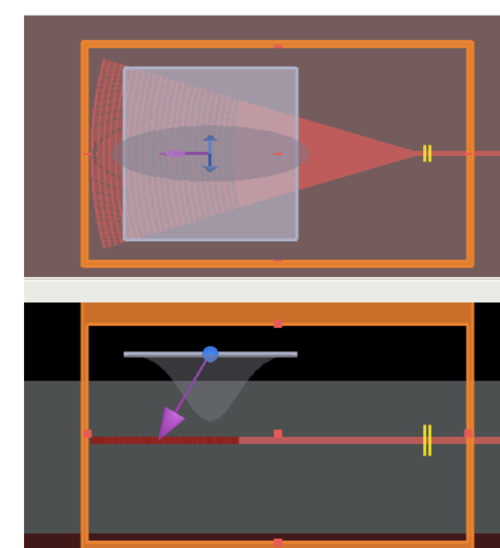
Mask Layout import



Layout drawing using Layout model in Pyxis

Design Verification

3D FDTD simulation



Simulations

SWG TE & TM

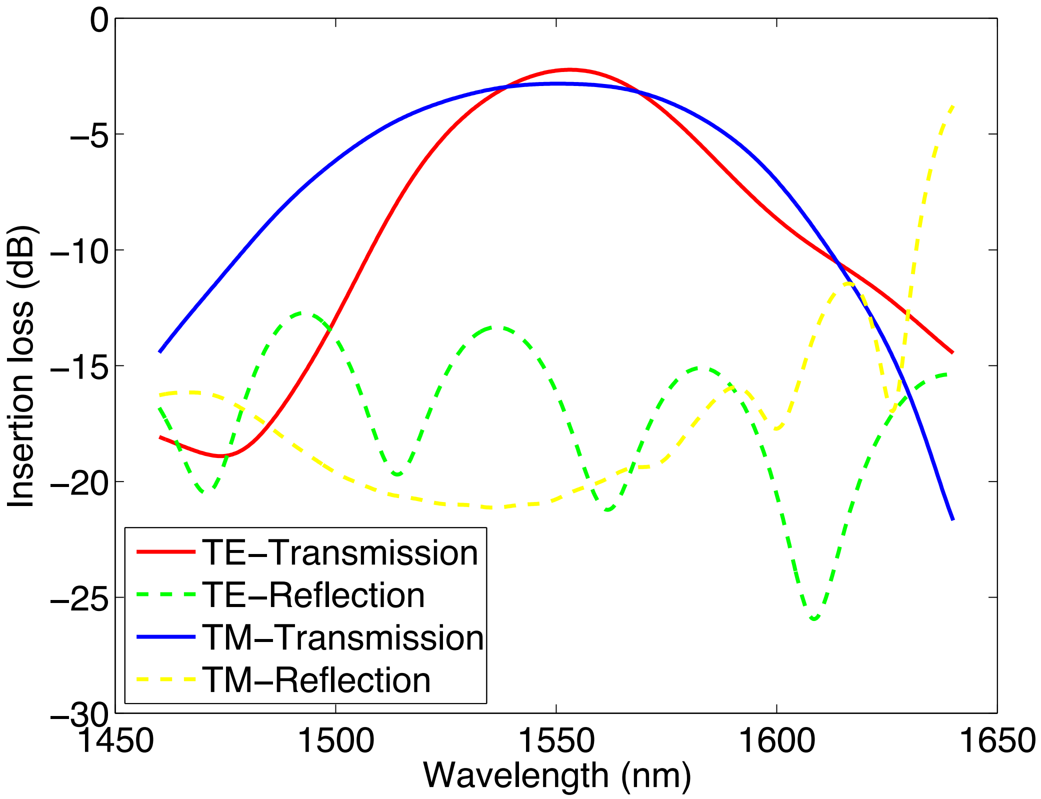


Fig. 10. Simulated transmission and reflection spectra of fully-etched sub-wavelength gratings couplers for the fundamental TE and the fundamental TM modes.

Shallow-etched vs. SWG GC

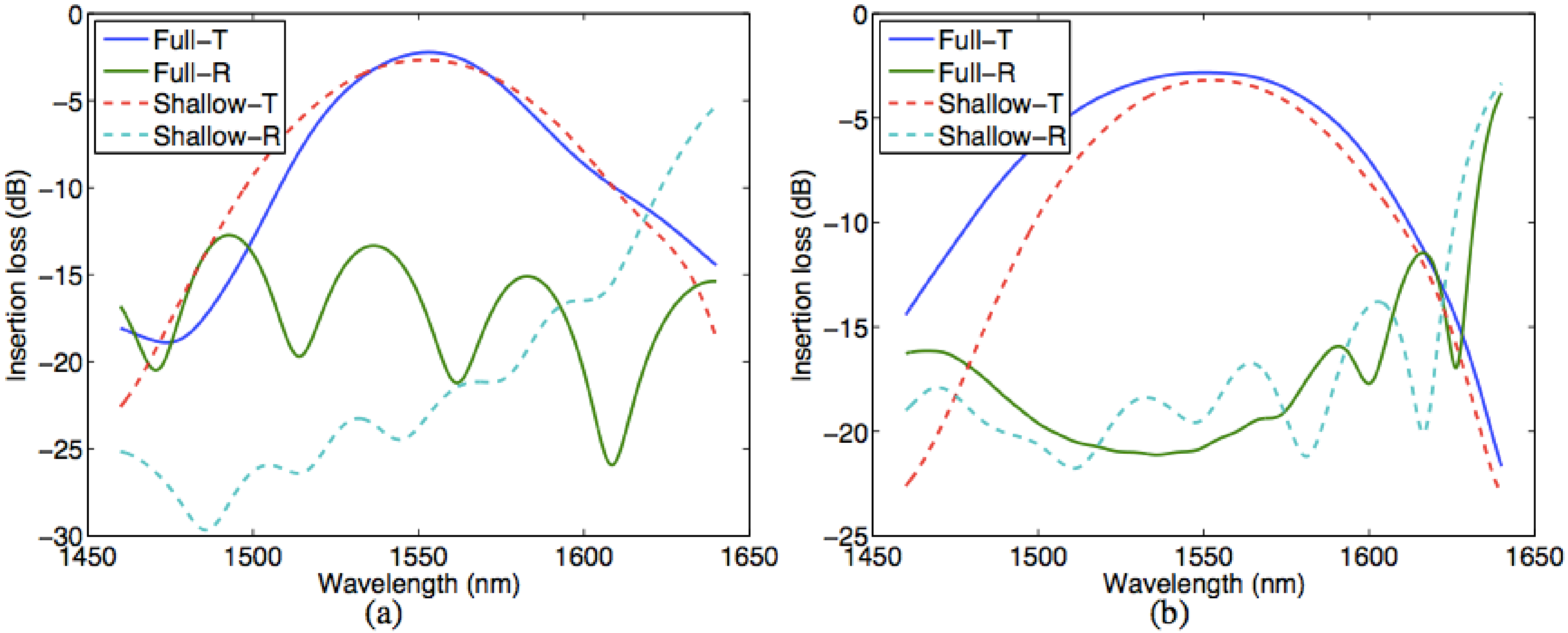


Fig. 11. (a) Simulated transmission and reflection spectra for the optimized fully-etch sub-wavelength grating coupler and the shallow-etched grating coupler with uniform grating for the fundamental TE mode; (b) simulated transmission and reflection spectra for the optimized fully-etched sub-wavelength grating coupler and the shallow-etched grating coupler with uniform grating for the fundamental TM mode.

- *Full-T denotes the transmission spectrum of the fully-etched SWG GC with uniform gratings;
- *Full-R denotes the reflection spectrum of the fully-etched SWG GC with uniform gratings;
- *Shallow-T denotes the transmission spectrum of the shallow-etch GC with uniform gratings;
- *Shallow-R denotes the reflection spectrum of the shallow-etch GC with uniform gratings;

- SWG TE GC have comparable coupling efficiency, back reflection, and bandwidth;
- SWG TM GC have better coupling efficiency, lower reflection, and broader bandwidth;
- Simulation based on uniform gratings without apodization;

Setup and measurement

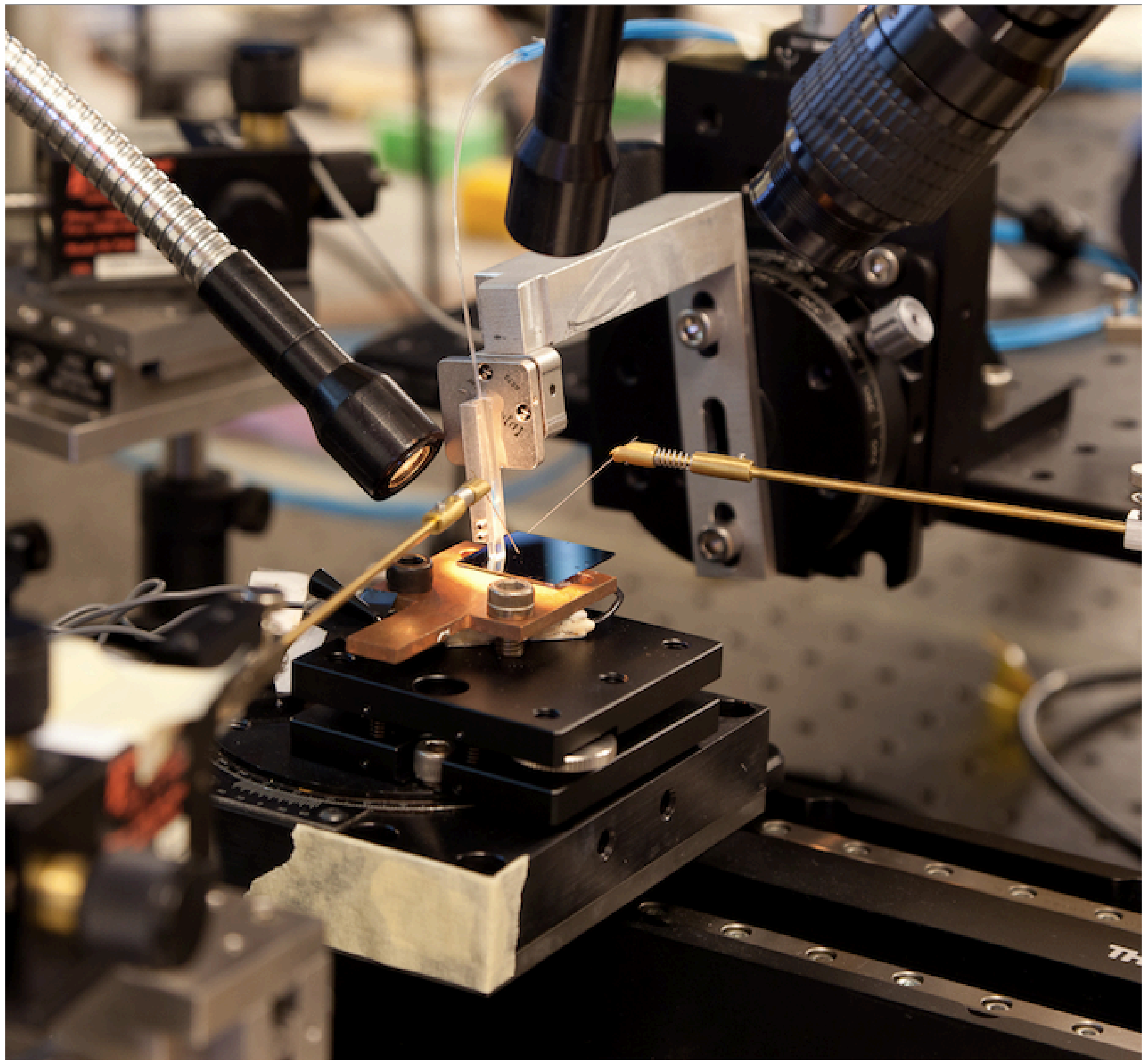


Fig.12 Chip-scale automated silicon photonics measurement setup 1

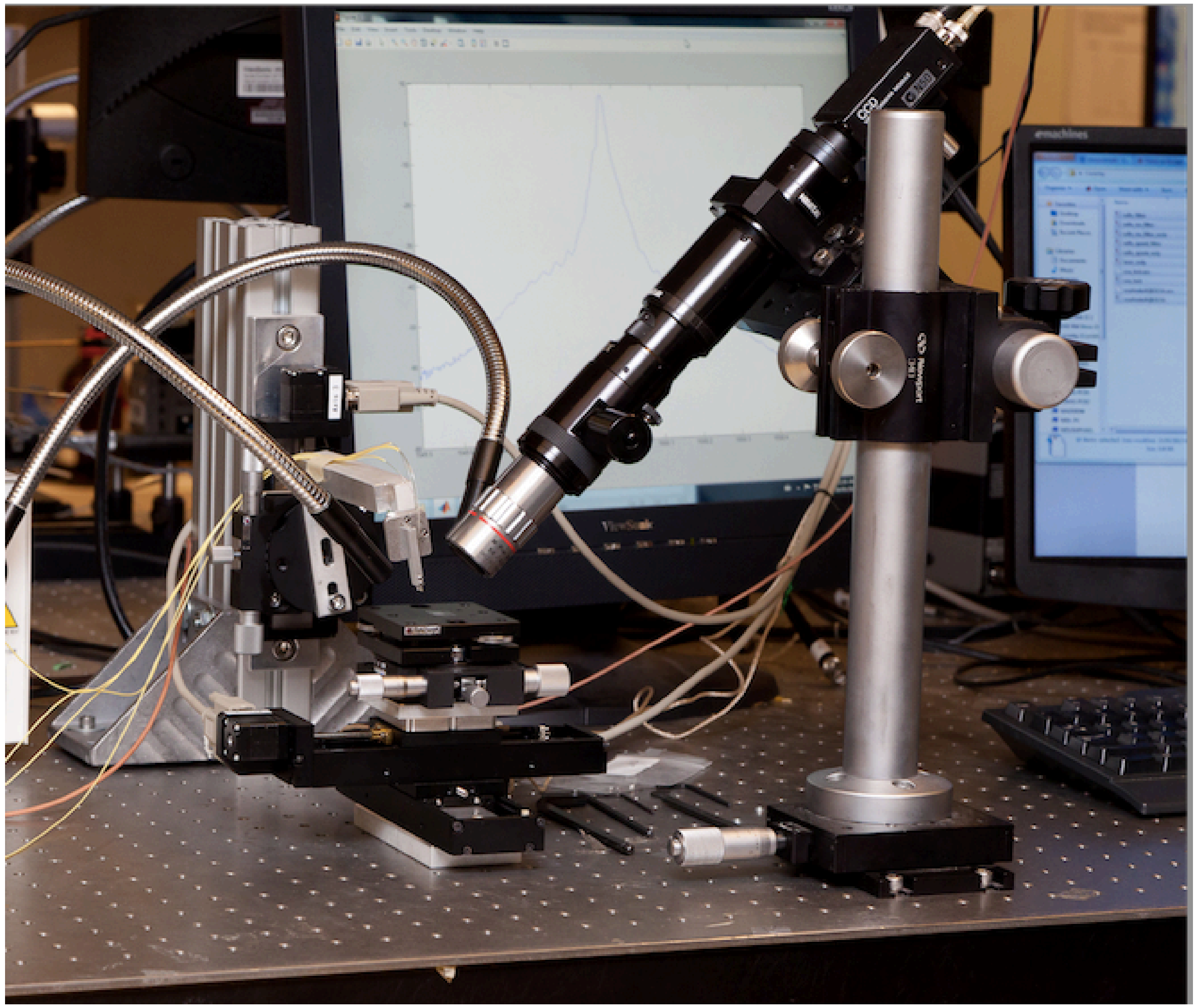


Fig.13 Chip-scale automated silicon photonics measurement setup 2

- Chip-scale automated measurement setup enables high-volume measurement for passive-only devices ;
- Versatile fibre-ribbon accommodates for various incident angle;
- Compatible for bio-fluidic measurement & active measurement;

Setup and measurement

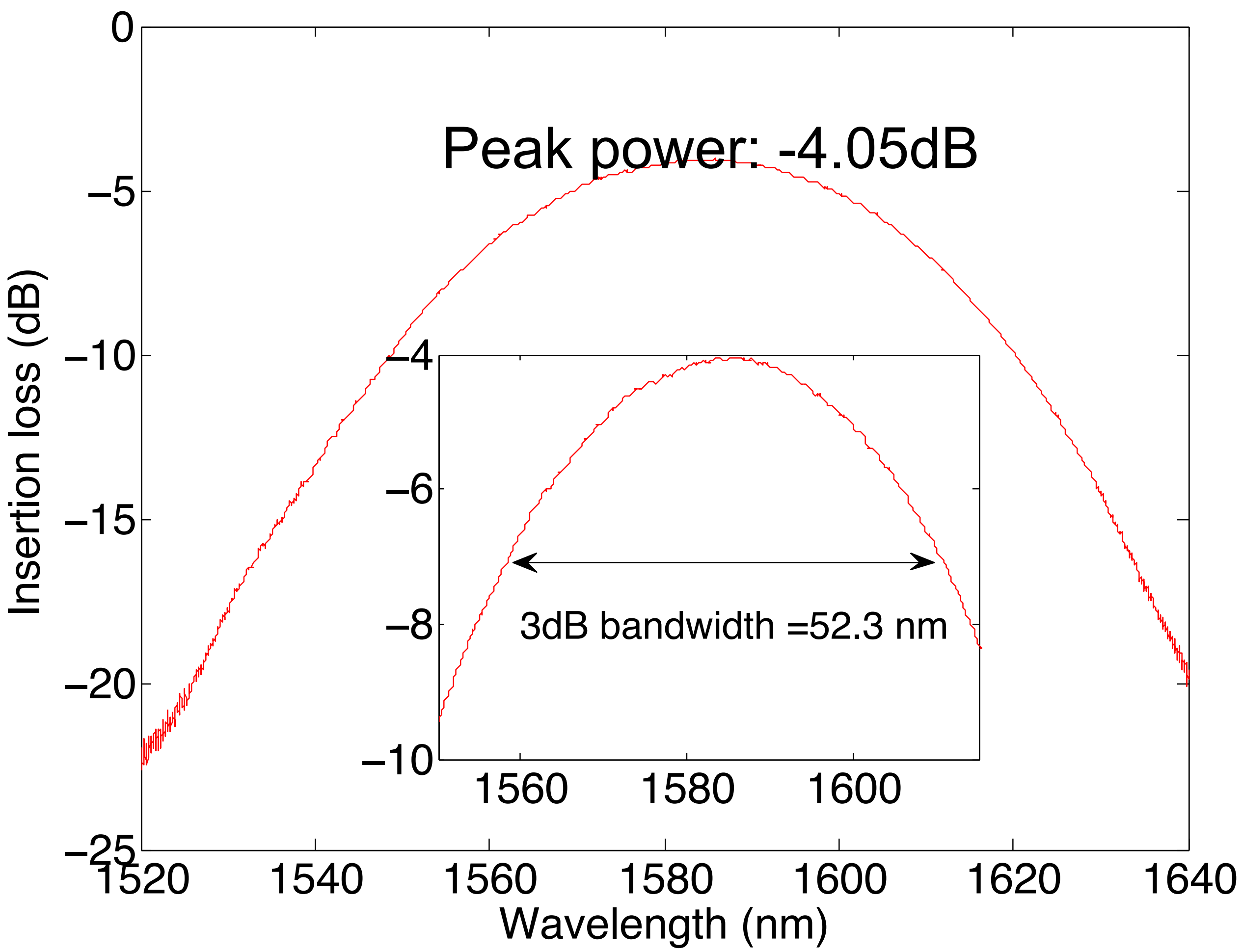


Fig.11 Measured transmission spectrum of a single sub-wavelength grating coupler for TE00 mode.

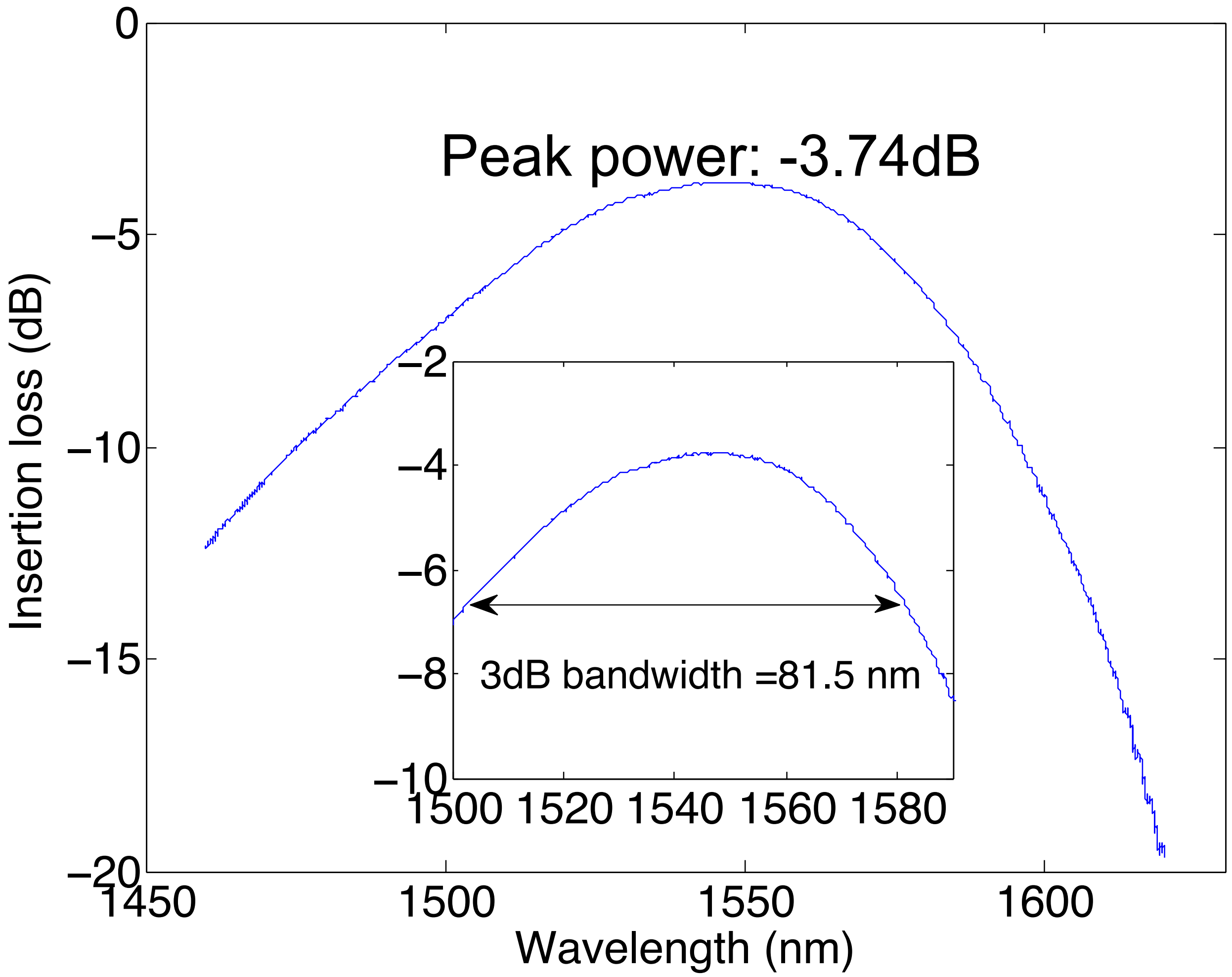


Fig.12 Measured transmission spectrum of a single sub-wavelength grating coupler for TM00 mode.

*Measure results are directly extracted from measured spectra for a GC pair, without calibrating any loss from the measurement system; no matching index liquid is used for the measurement;
More measurement results and analysis can be found in [2].

[2]. Yun Wang, Xu Wang, Jonas Flueckiger, Han Yun, Wei Shi, Richard Bojko, Nicolas A.F. Jaeger, and Lukas Chrostowski , "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonics circuits", OE, 2014

Future work

- Future work can be done by apply apodizations to the sub-wavelength grating couples in order to get better mode overlap between the fibre and the gratings;
- The simulated minimum insertion losses for the apodized sub-wavelength TE and TM grating couplers are 1.6 dB and 1.9 dB, which are comparable to the state-of-the-art shallow-etched grating coupler without bottom mirrors or top overlays.
- Bottom mirror can be applied to further improve the coupling efficiency, with a bottom metal mirror the simulated insertion loss of the SWG for both TE and TM mode can be as low as 0.45dB per coupler;

Summary

- We demonstrate sub-wavelength grating couplers for both transverse electric (TE) and transverse magnetic (TM) modes;
- Focusing grating lines have been used to reduce the overall footprint of the design;
- Back reflections from the regular fully-etch grating coupler have been highly suppressed by using the sub-wavelength structure;
- It's also shown by both simulation and fabrication results that sub-wavelength grating lines have advantages over the sub-wavelength quasi-squares;
- A measured -4.05 dB insertion loss with a 3-dB bandwidth of 52.3nm have been achieved for TE mode and a measured -3.74 dB insertion loss with a 3-dB bandwidth of 81.5nm have been achieved for TM mode.

Acknowledgement

- This work was supported by the Natural Sciences and Engineering Research Council of Canada, particularly under the CREATE SiEPIC program.
- The devices were fabricated at the University of Washington Washington Nanofabrication Facility (WNF), part of the National Science Foundations National Nanotechnology Infrastructure Network (NNIN).
- We acknowledge Lumerical Solutions, Inc., and Mentor Graphics for the design software.

Thank You !