Response Tailoring of Silicon Integrated Bragg Gratings

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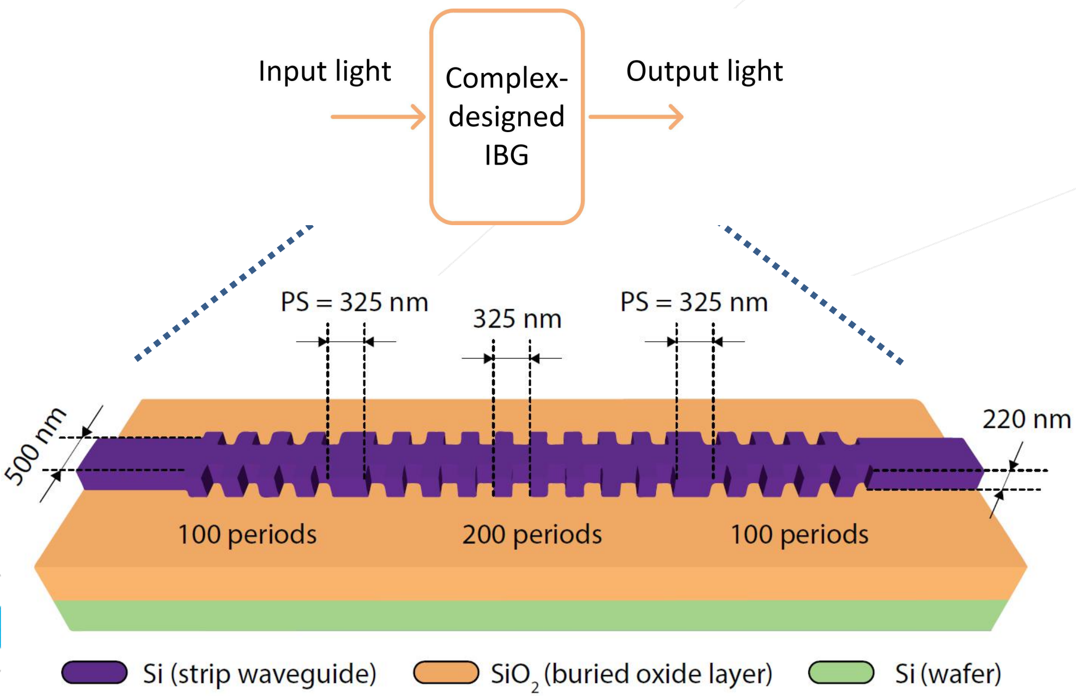
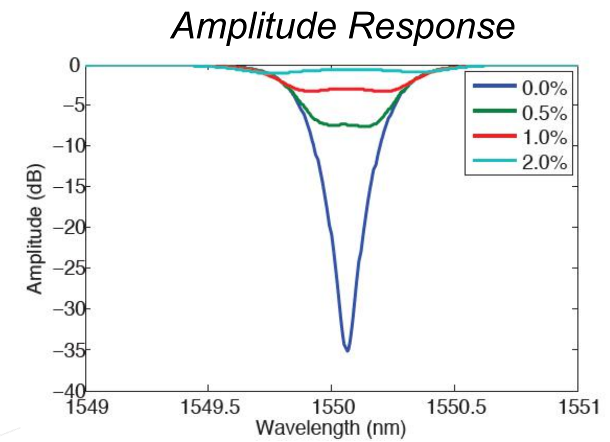
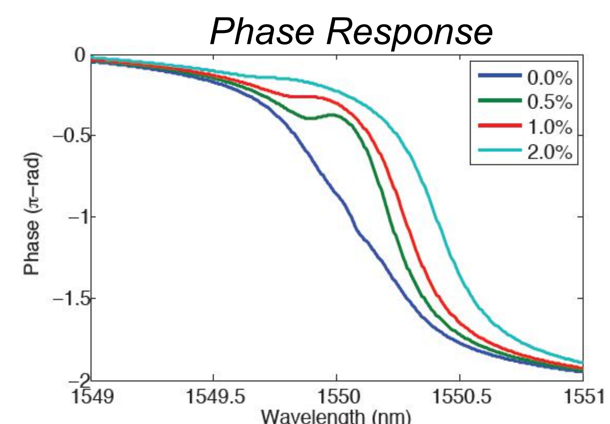
Flexible reflection response of integrated Bragg gratings (IBGs)

Silicon IBGs have **extremely high flexibility** in tailoring amplitude & phase reflection response

- Versatile filers in WDM systems
- Microwave photonic signal processing
- Optical signal precessing
- Communication networks







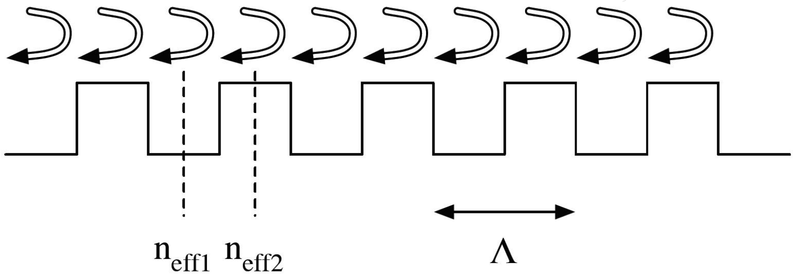
Burla, Maurizio, et al. Optics express 21.21 (2013): 25120-25147.

Basic principle of tailoring IBG responses

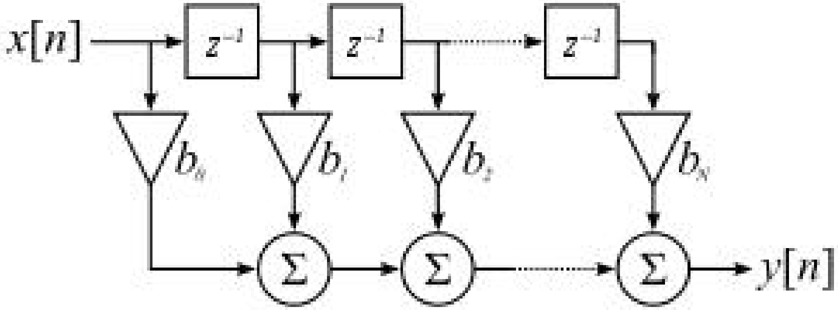
IBG reflection response can be freely tailored by modulating the grating strength, κ, and phase along the grating

- IBG reflection response is essentially determined by the summation of the distributed optical feedbacks
- analogous to a finite impulse response (FIR) filter

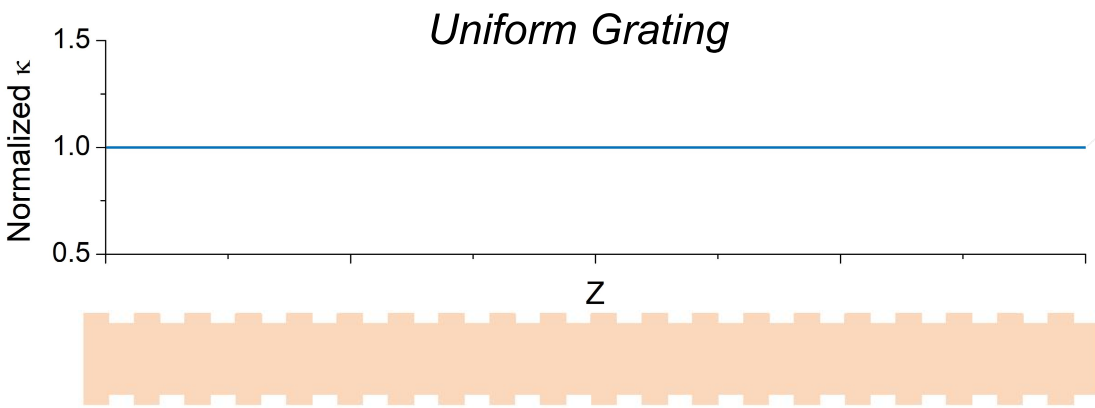
Distributed optical feedback

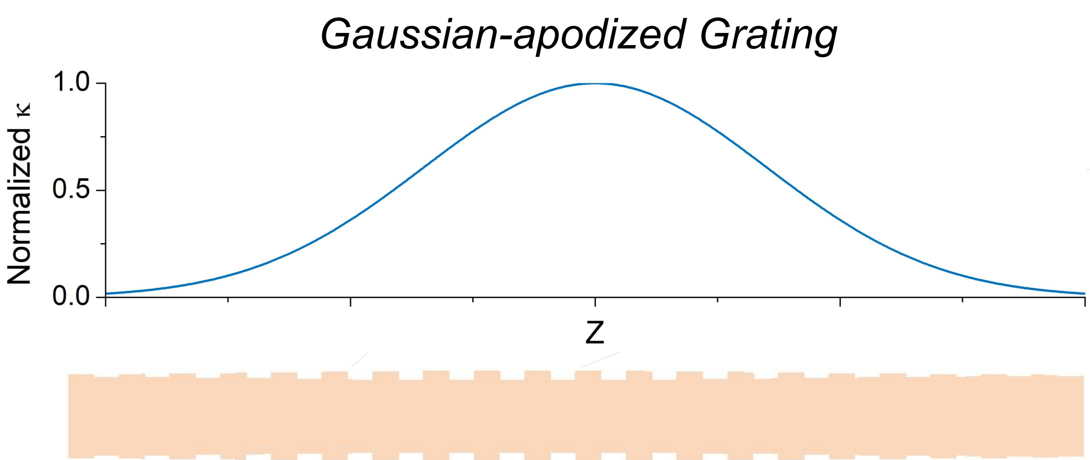


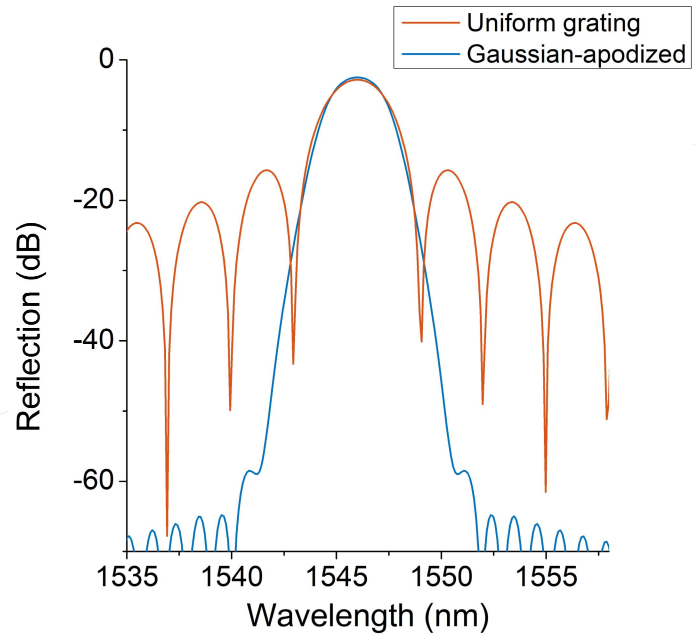
FIR filters



The simplest example of IBG spectral tailoring: Gaussian-apodized gratings

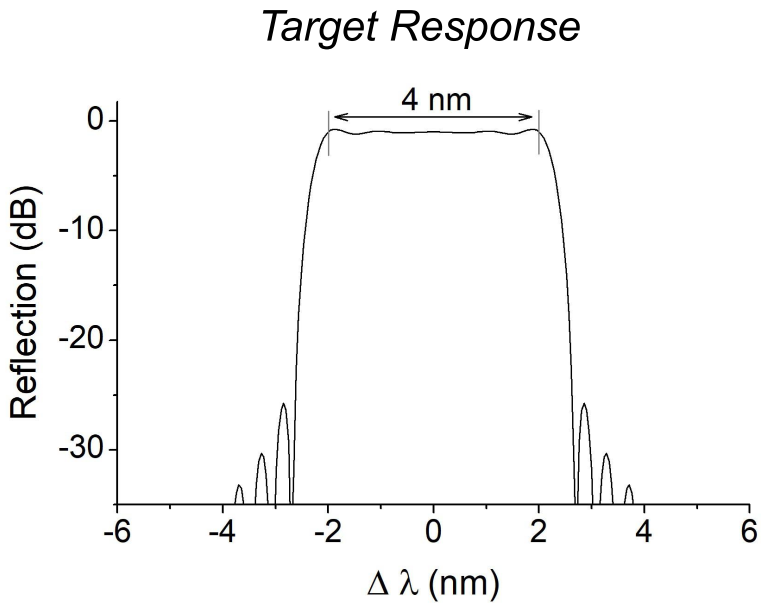






Design of arbitrary responses on silicon IBGs

When a more complex response is desired, how to design the IBG to achieve this response?



?

- κ(z) profile
- grating phase profile
- corrugation width
- grating physical structure

......

Grating strength and phase profiles calculation

First, once a target response is decided, how to calculate the required grating strength and phase profiles?

√

?

$r(\lambda)$ → $\kappa(z)$ & $\varphi_g(z)$

Target spectral response

Grating strength and phase profiles

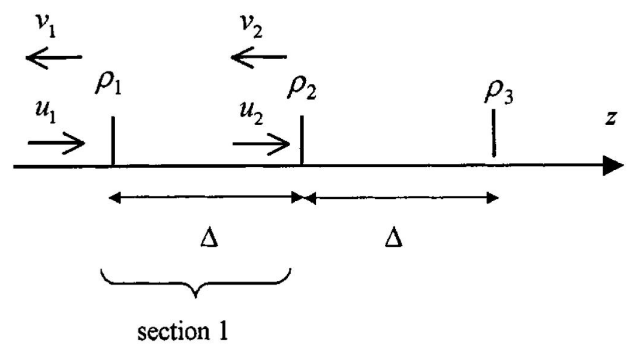
Layer peeling algorithm

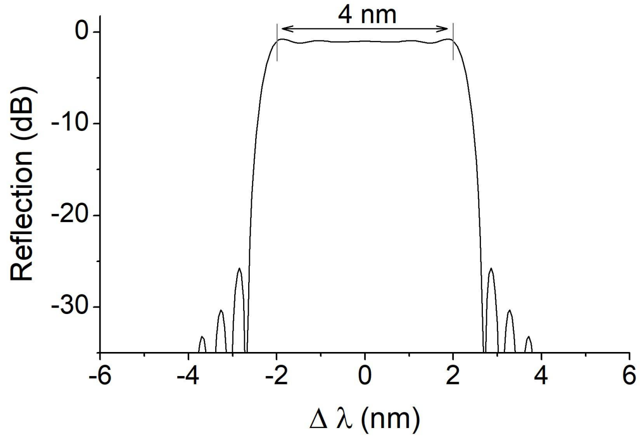
- Layer peeling algorithm (LPA) [1]
  - An inverse scattering algorithm
  - to calculate the required grating κ(z) and phase profile from the target response

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 37, NO. 2, FEBRUARY 2001 165

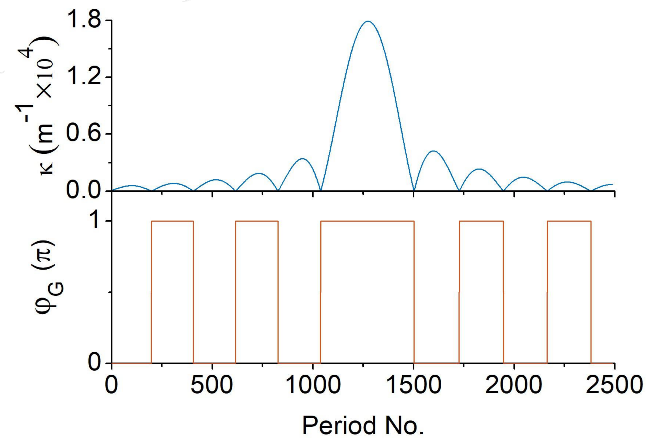
On the Synthesis of Fiber Bragg Gratings by Layer Peeling

Johannes Skaar, Ligang Wang, and Turan Erdogan





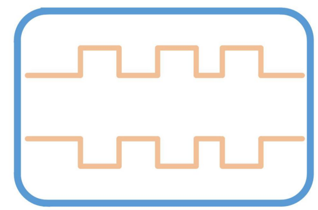
LPA



1. J. Skaar L. Wang, and T. Erdogan. IEEE Journal of Quantum Electronics 37.2 (2001): 165-173.

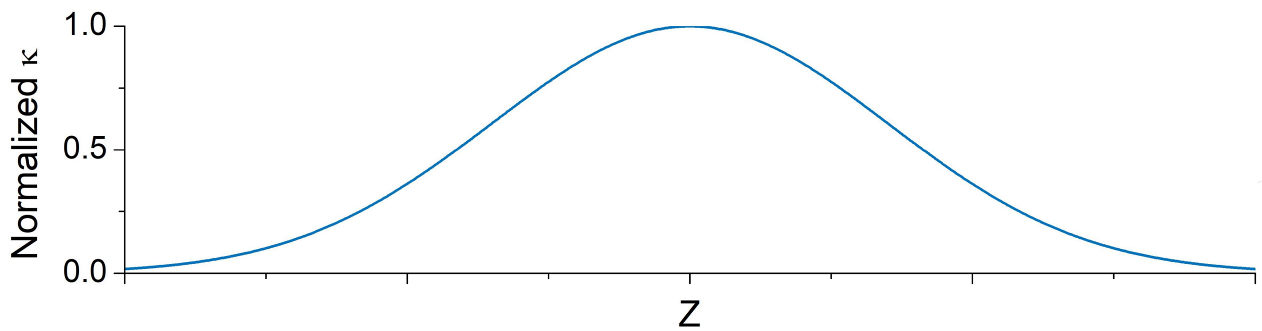
Structure determination

Once the required grating strength and phase profiles are known, how to create the corresponding grating structure?

√		√	?	
$r(\lambda)$	*LPA* →	$\kappa(z)$ & $\varphi_g(z)$	→	
Target spectral response		Grating strength and phase profiles		Grating Structure

κ(z)-to-structure conversion through apodization

- A κ(z) profile can be mapped into a grating physical structure through **apodization**
- Apodization: **control of κ by modifying the grating structure**



Apodization through modulating corrugation width, ΔW

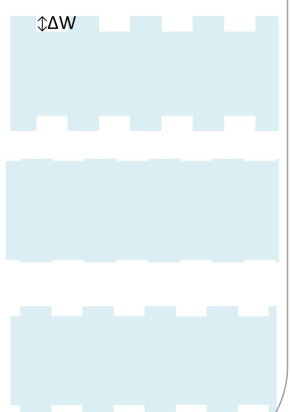
Apodization of integrated Bragg gratings

Common apodization schemes

Corrugation width ΔW modulation

Pros:
- straightforward;
- easy to draw；

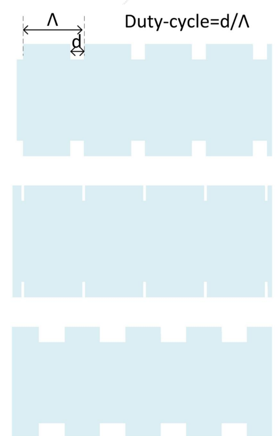
Cons
- low resolution
- low dynamic range



Duty-cycle modulation

Pros:
- improved resolution and dynamic range

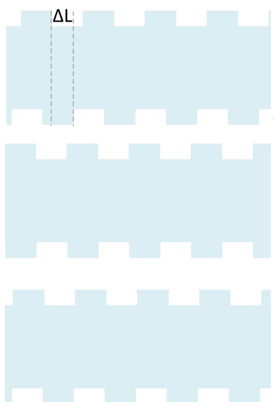
Cons
- lead to Δn_{eff} variations



Lateral missalignment modulation

Pros:
- improved resolution and dynamic range

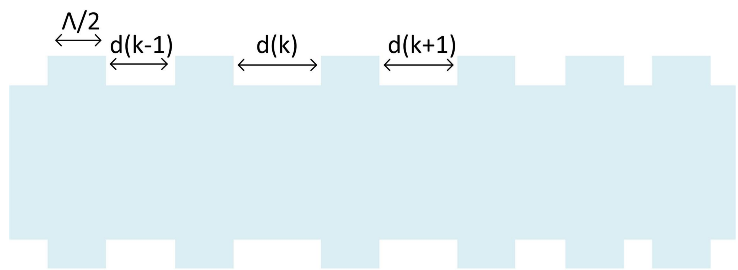
Cons
- lead to Δn_{eff} variations



Phase modulation

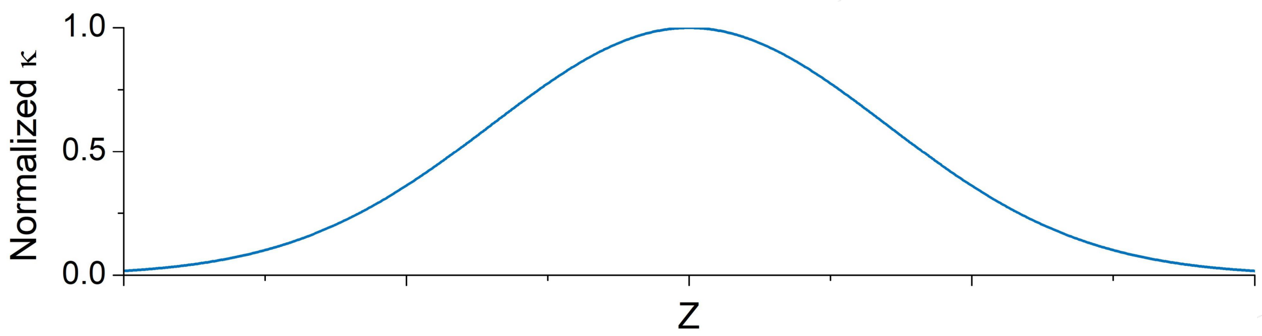
Pros:
- high resolution and dynamic range;
- low Δn_{eff} variations；

Cons
- high spectral noise floor;
- echoes at the two sides of the Bragg resonance;
- high implementation complexity;



Apodization of integrated Bragg gratings

- Different apodization methods lead to entirely different grating structures

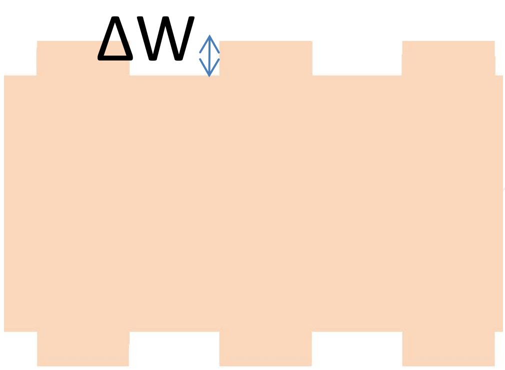


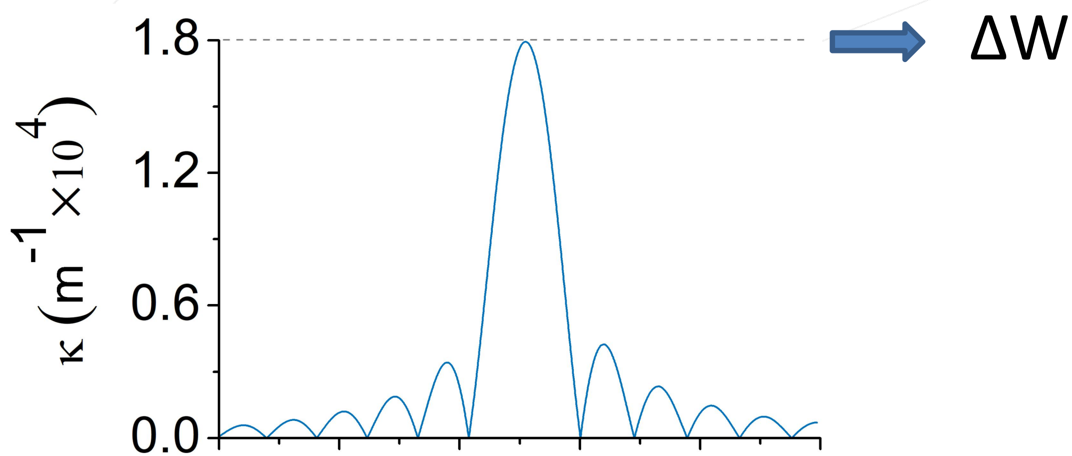
Duty cycle modulation

Misalignment modulation

Corrugation-width determination

- Most apodization methods will modulate the relative κ distribution along the grating, with ΔW remaining constant
- the amplitude of the κ distribution will be determined by ΔW
- ΔW thus should be selected according to maximum value of κ(z)



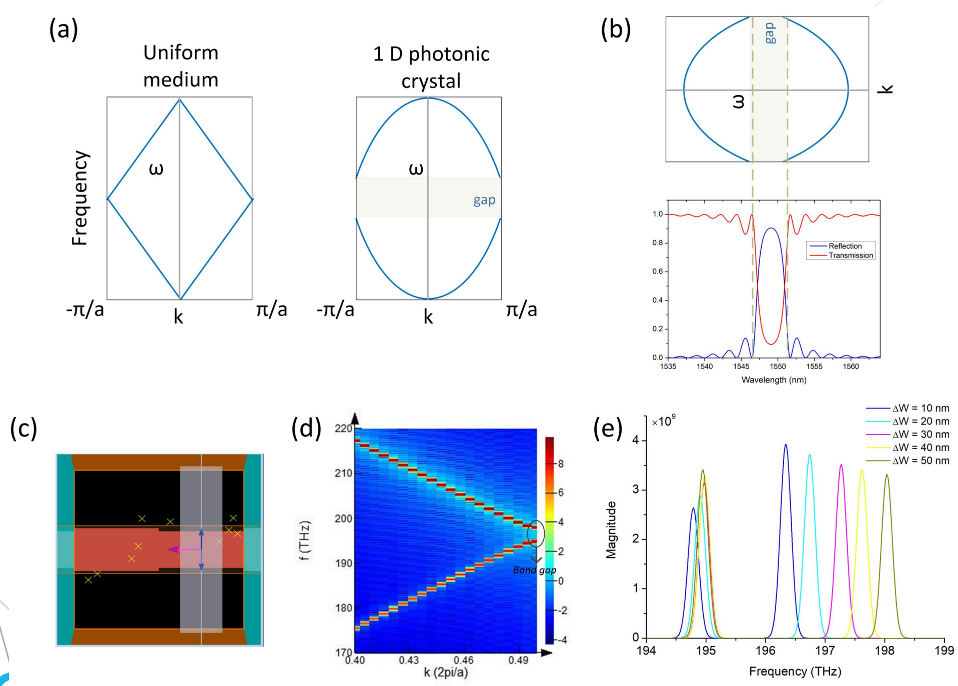


Finding relationship between κ and ΔW

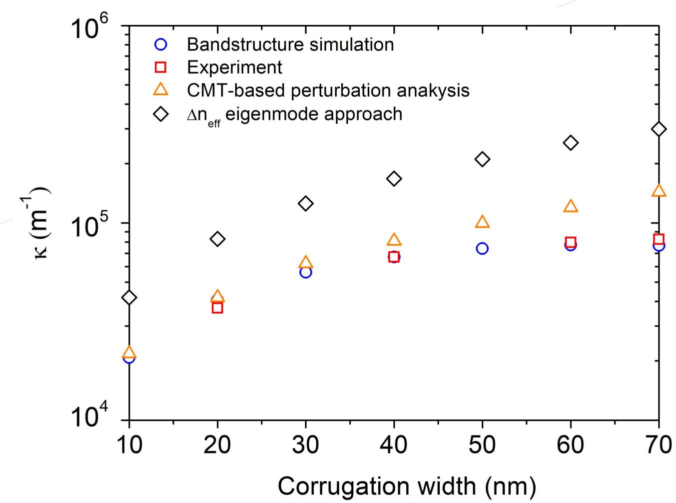
Methods

- **Band-structure calculation through 3D-FDTD**
- **Extracted from experimental results**
- CMT-based perturbation analysis: $\kappa = \frac{k_0^2}{2\beta N^2}\int_{\text{Corrugation}} \Delta[n^2(x,z)]\varepsilon^2(x)dx$

Bandstructure calculation



Comparison of κ calculation results for different methods

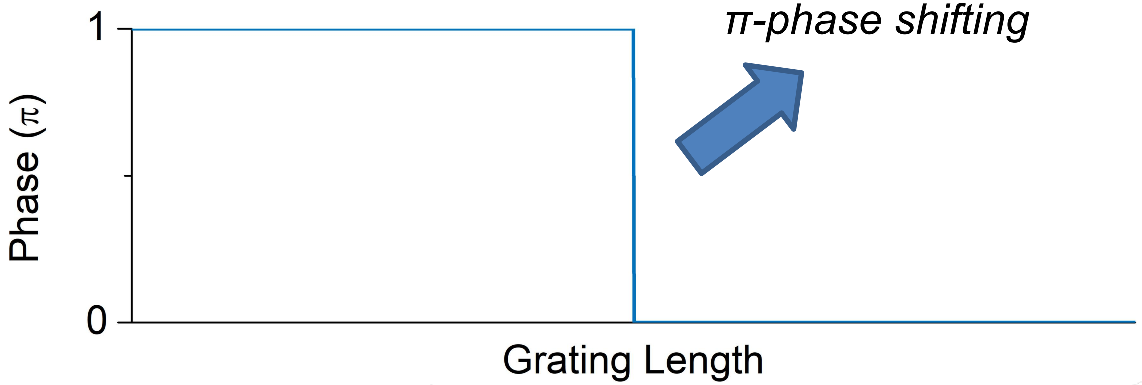


S. Kaushal, et al. Frontiers of Optoelectronics 11.2 (2018): 163-188.

Computer Engineering

a place of mind

Phase-to-structure conversion

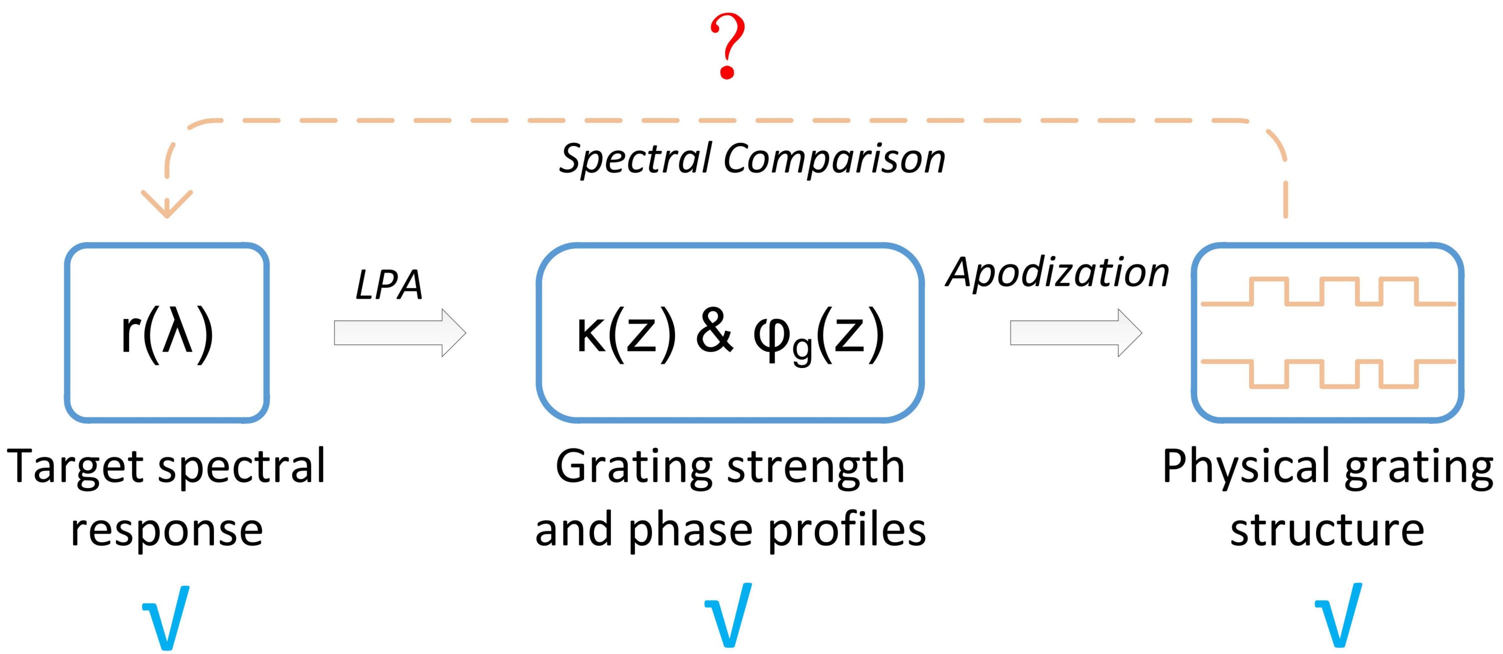


π-phase shifting

Introduce an additional half-period long corrugation

Structure-aware grating modeling

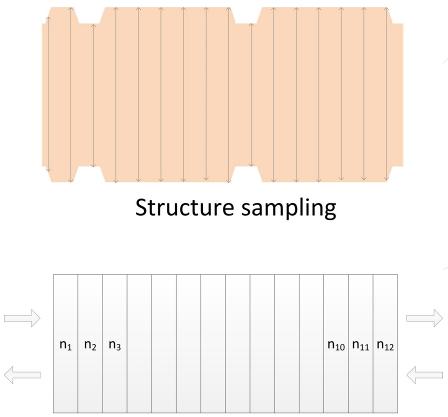
- When the whole grating structure is determined, how to check if the corresponding response will be consistent with our design?



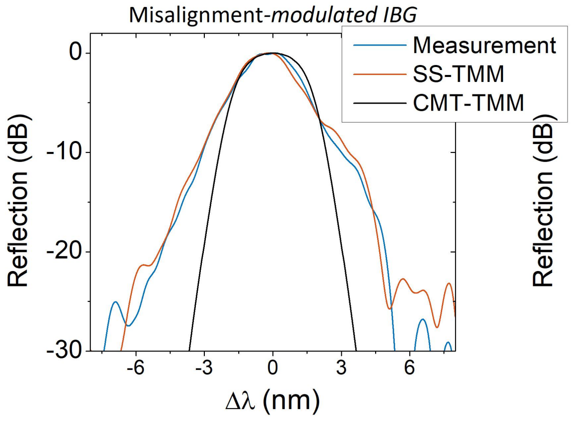
Structure-aware graing modeling methods

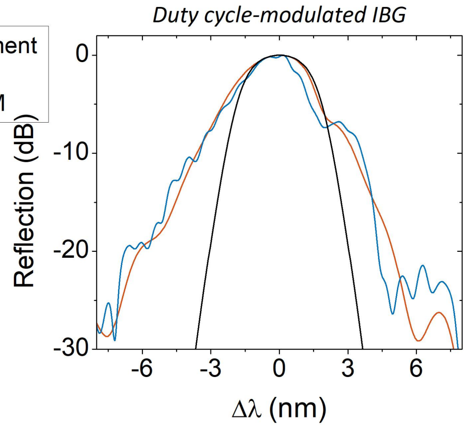
- Common structure-aware modeling methods for apodized IBG
  - **Structure-synthesis-based transfer matrix method (SS-TMM)** [1]
  - 2D/3D FDTD
  - Bidirectional eigenmode expansion (EME) solver
- SS-TMM
  - An efficient and accurate modeling tool for apodized IBGs
  - Take into account Δn_{eff} due to structure modifications for apodization

Structured sythesis-based TMM （SS-TMM）



Equivalent multiplayer structure



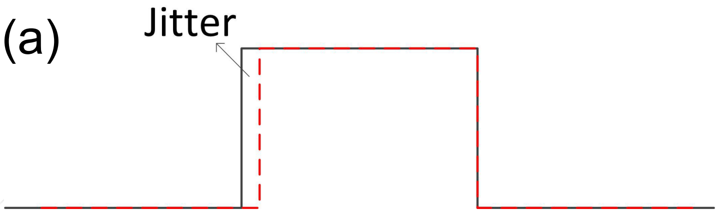


1. R. Cheng, Y. Han, and L. Chrostowski. Optics Express 27.7 (2019): 9516-9535.

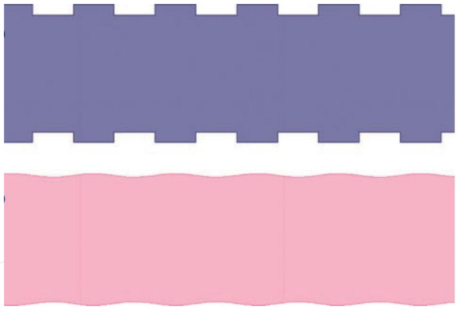
Fabrication issues of IBGs on silicon

- Fabrication limitations and uncertainties
  - Lithography writing jitters (a)
  - Fabrication non-uniformity
    - SOI thickness variations
    - waveguide width variations
    - etch non-uniformity
  - Lithography smoothing effect (b)
  - Quantization errors to the grid size (c)
  - Minimum realizable feature size/spacing (d)

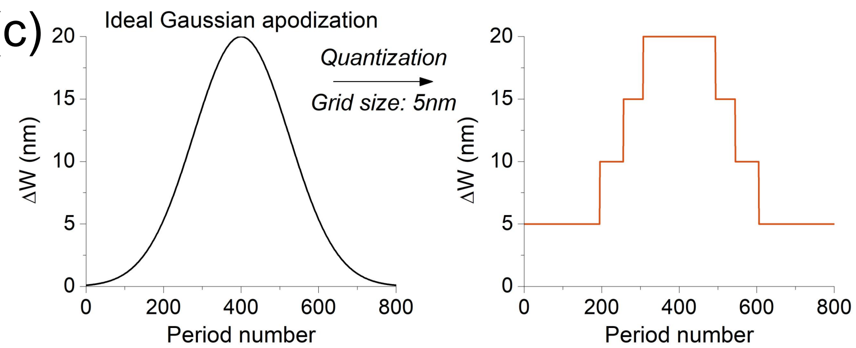
(a)



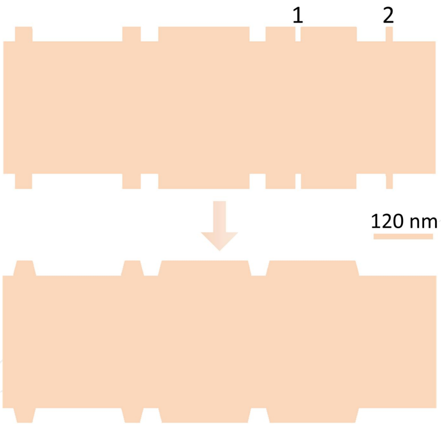
(b)



(c)



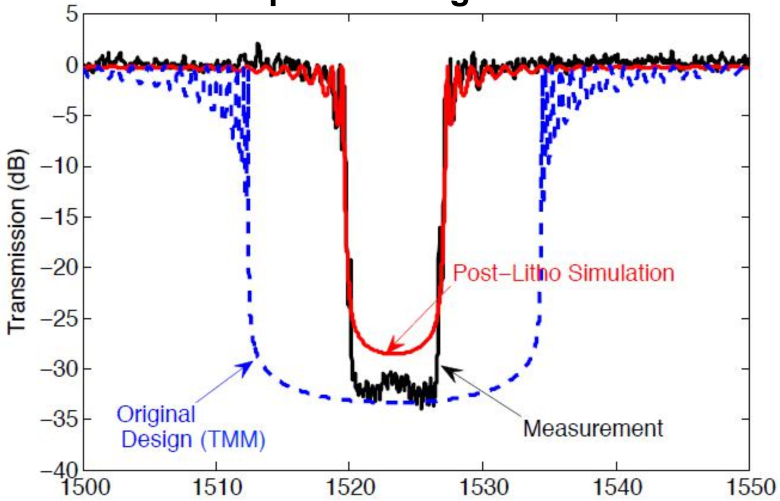
(d)



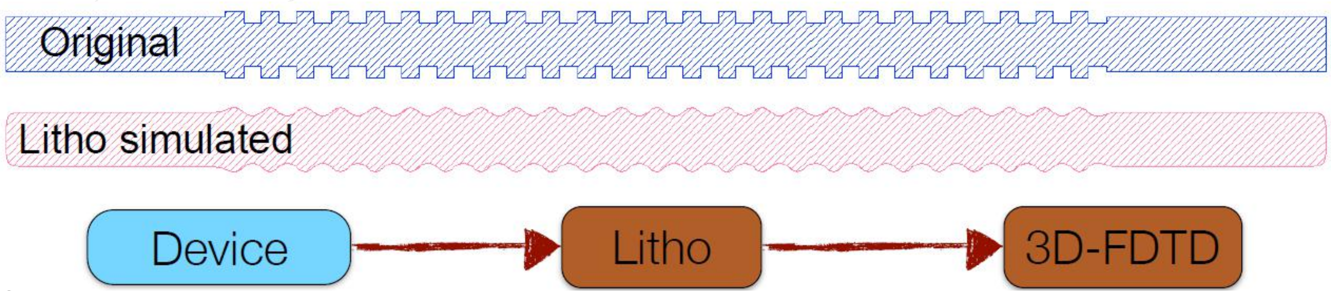
Lithography model for predicting actual grating responses

- Lithography model to modify the grating structures to be closed to the actually fabricated ones
- Combine a grating structure-aware modeling method (such as 3D-FDTD) with a lithography model
  - Include fabrication limitations in the simulations
  - Better predict the actual grating spectrum

Comparison of a grating with 40 nm square corrugations



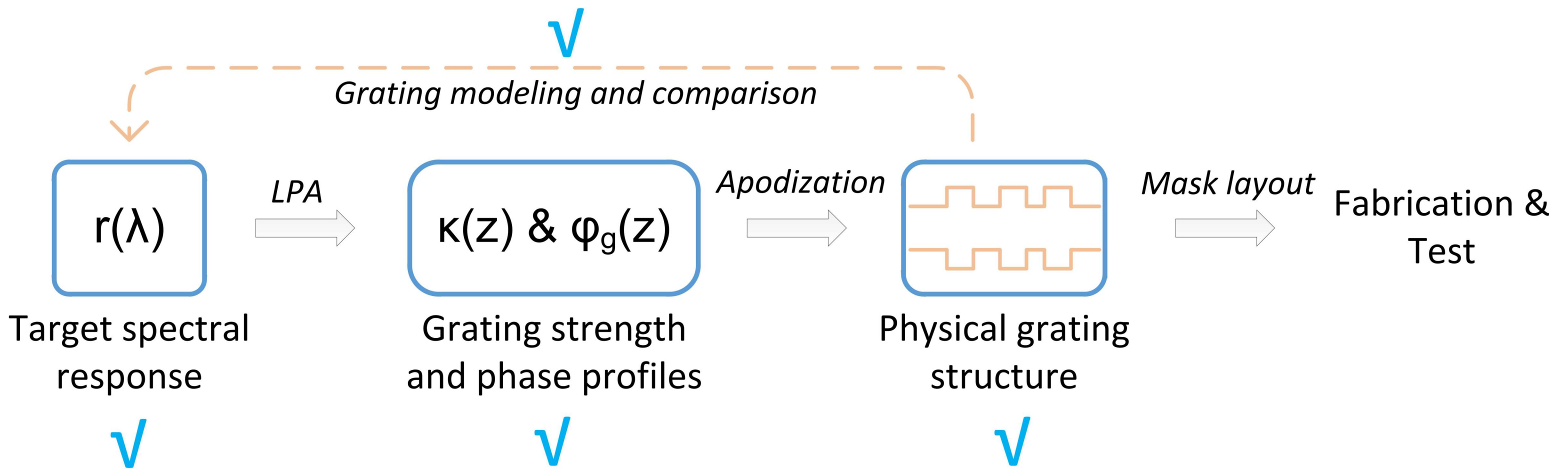
Wang, Xu, et al. The 9th International Conference on Group IV Photonics (GFP). IEEE, 2012.



place of mind

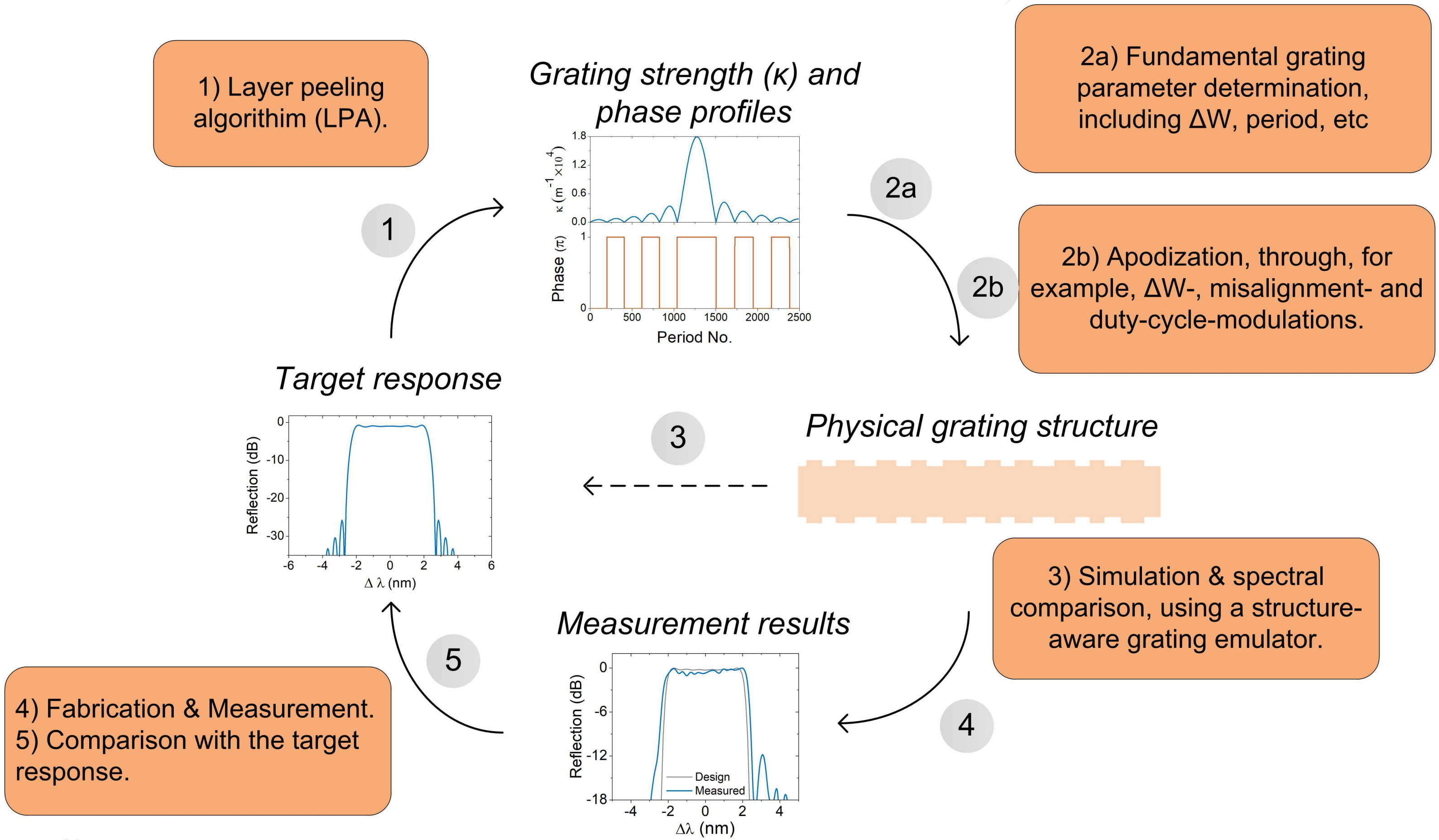
Completing a design cycle of an IBG

- Finally, the designed gratings are send for the fabrication, followed by the experimental test.



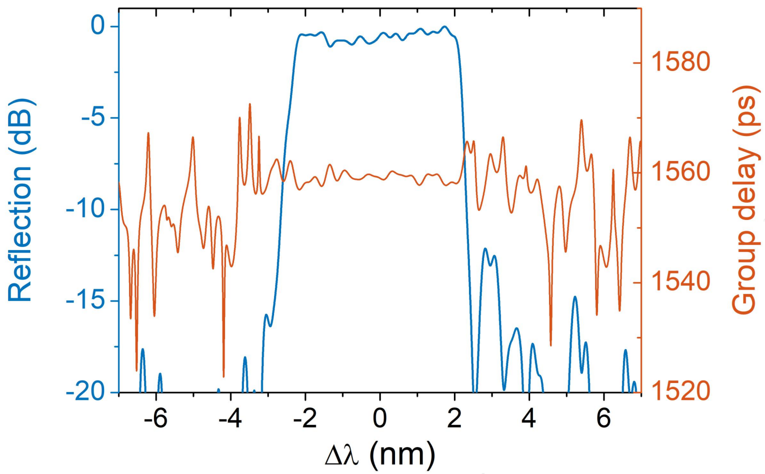
Silicon IBG design process summarization

Design flow of an IBG to achieve an arbitrary complex response

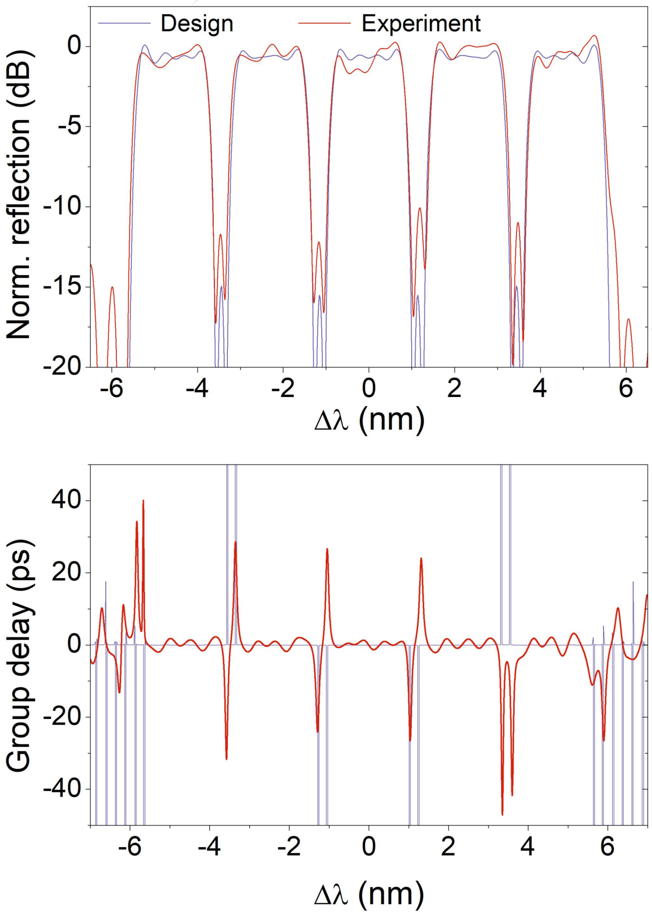


Examples of spectral tailoring of silicon IBGs

Square dispersion-free filter



5-channel square dispersion-free filter [1]



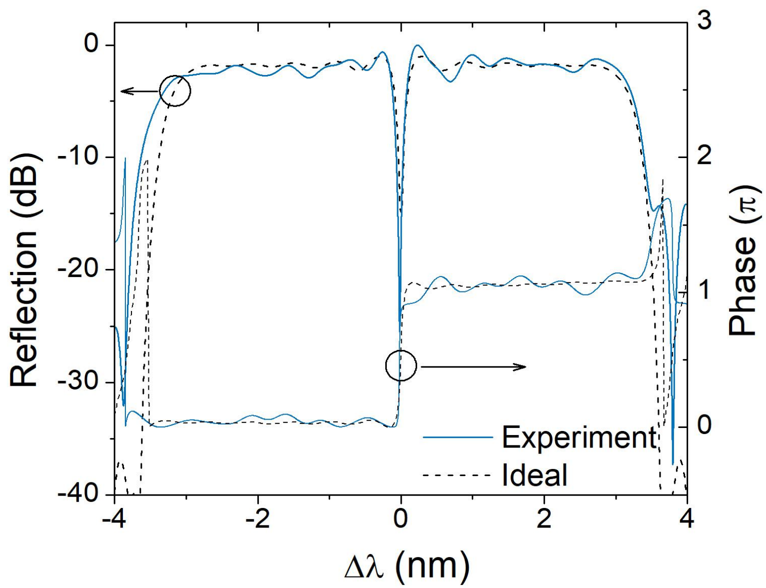
Electrical and Computer Engineering

a place of mind

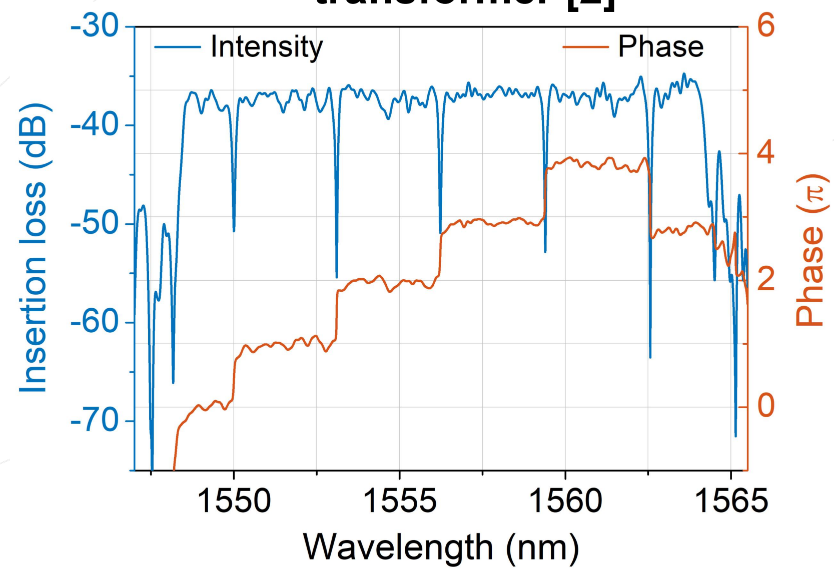
1. R. Cheng, H. Yun, S. Lin, Y. Han, and L. Chrostowski, Optics letters 44.2 (2019): 435-438.

Examples of spectral tailoring of silicon IBGs

Photonic Hilbert transformer [1]



Multi-channel photonic Hilbert transformer [2]



1. R. Cheng, Y. Han, and L. Chrostowski. Optics Express 27.7 (2019): 9516-9535.
2. R. Cheng, and L. Chrostowski. Optics letters 43 (5), 1031-1034.

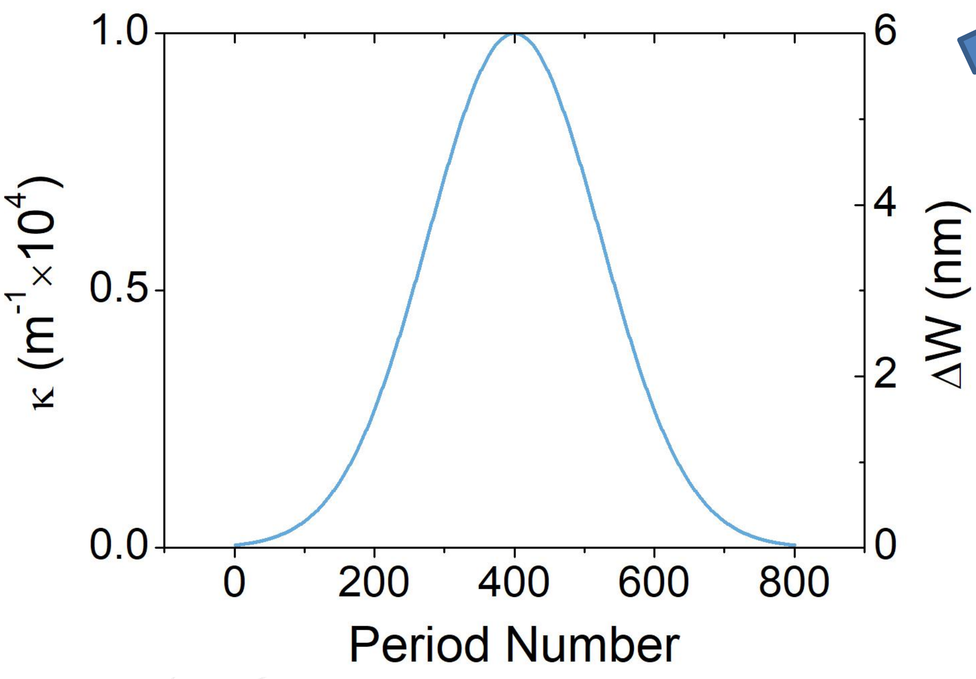
Further improvement of grating design

Techniques for further improvement of the grating design

- 1. $\kappa(z)$ profile amplification
- 2. transform long straight grating into more compact spiral shape
- 3. apodization phase noise compensation and grating spectral correction

κ profile amplification to relax fabrication constraints

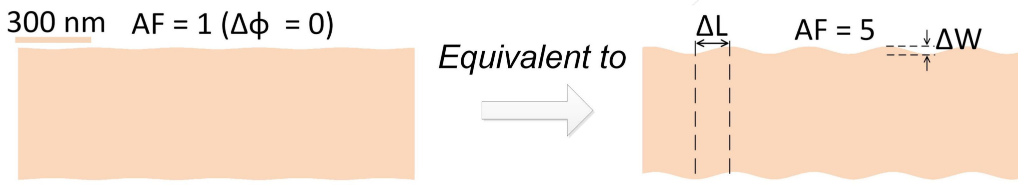
Consider to design a weak Gaussian-apodized grating using ΔW modulation

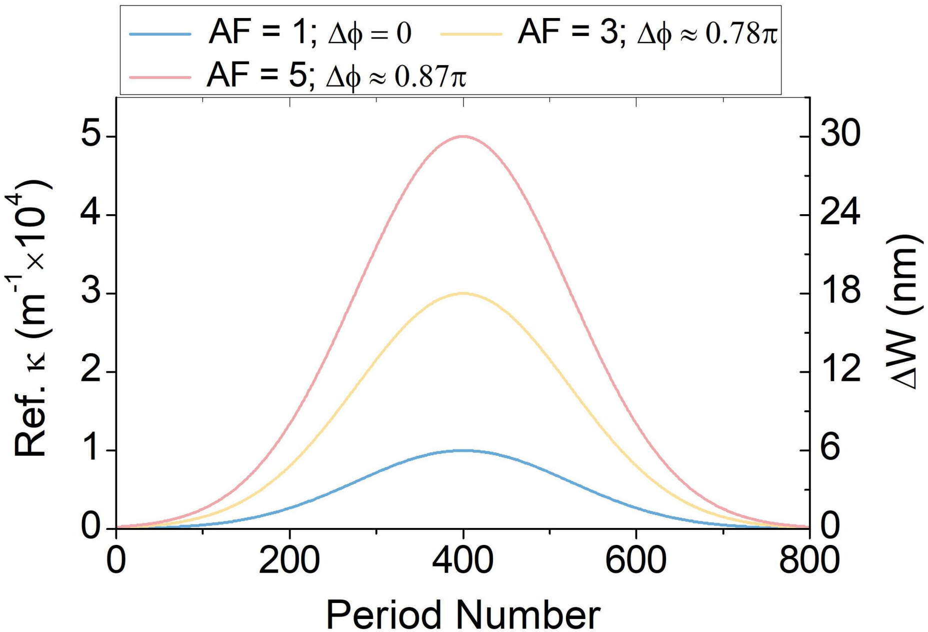


Almost cannot be realized practically! considered typical EBeam fabrication resolutions of 5 nm !

Apodization profile [κ(z)] amplification to overcome fabrication limitations

- κ(z) profile amplification through **lateral phase delay (Δϕ)**
  - introduce **Δϕ** to first make the grating weaker, and then use an scaled-up κ(z) to make the grating stronger





AF: amplification factor

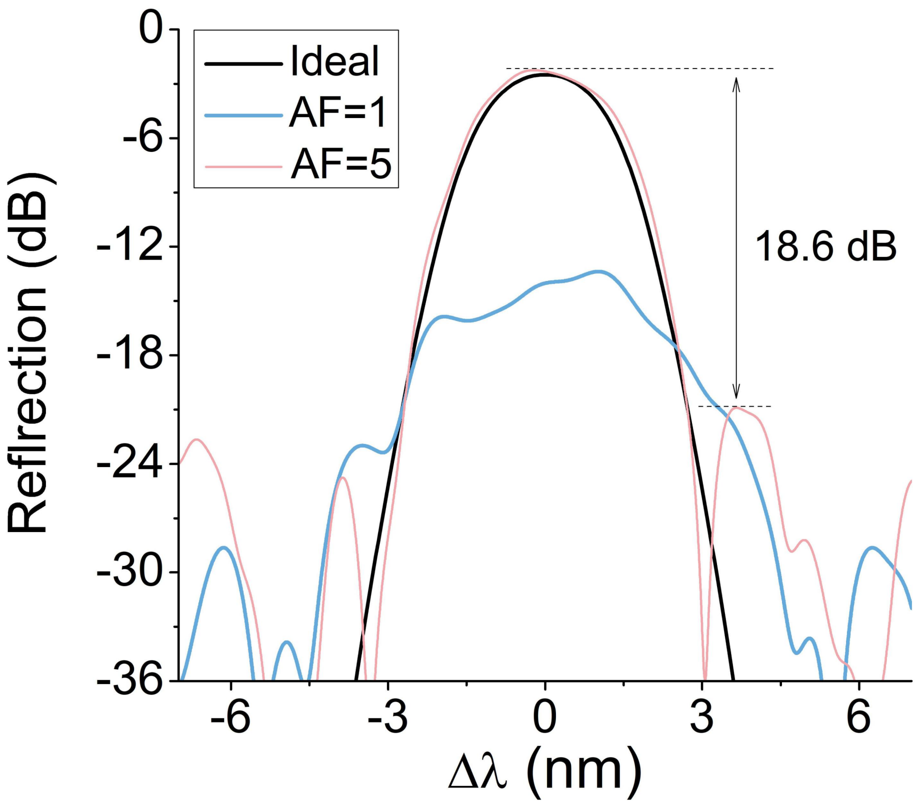
R. Cheng, H. Yun, S. Lin, Y. Han, and L. Chrostowski, Optics letters 44.2 (2019): 435-438.

Apodization profile [κ(z)] amplification to overcome fabrication limitations

- A significantly improved experimental spectral response

AF: amplification factor

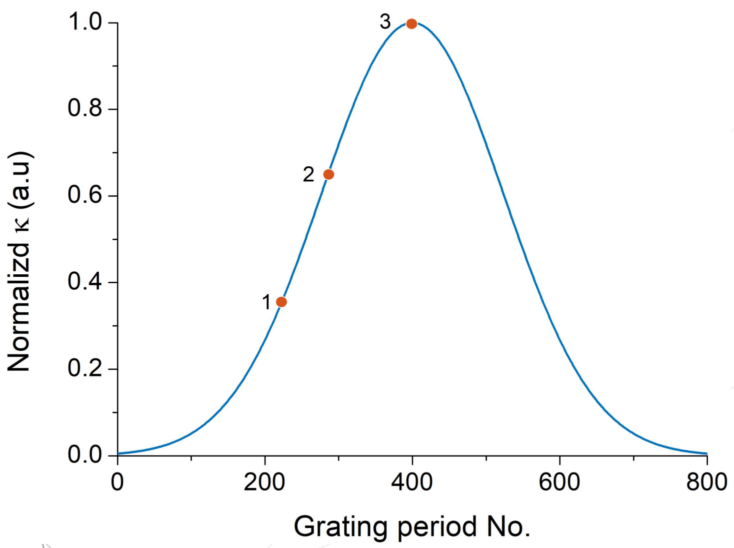
κ(z) amplification for a Gaussian-apodized corrugation-width modulated IBG

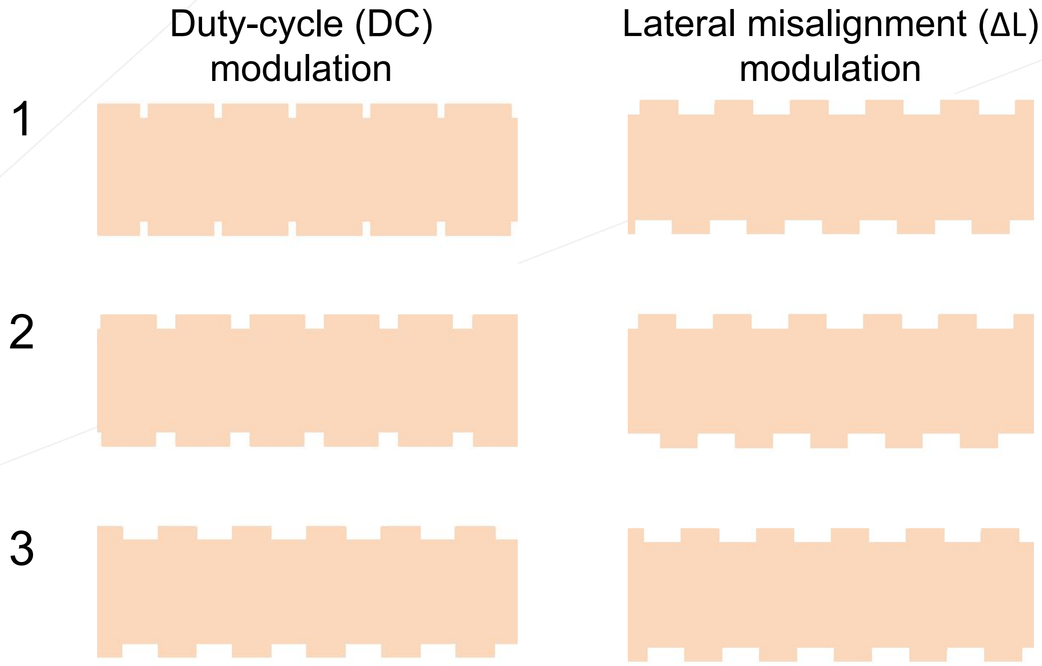


R. Cheng, H. Yun, S. Lin, Y. Han, and L. Chrostowski, Optics letters 44.2 (2019): 435-438.

Apodization phase noise (APN) issue

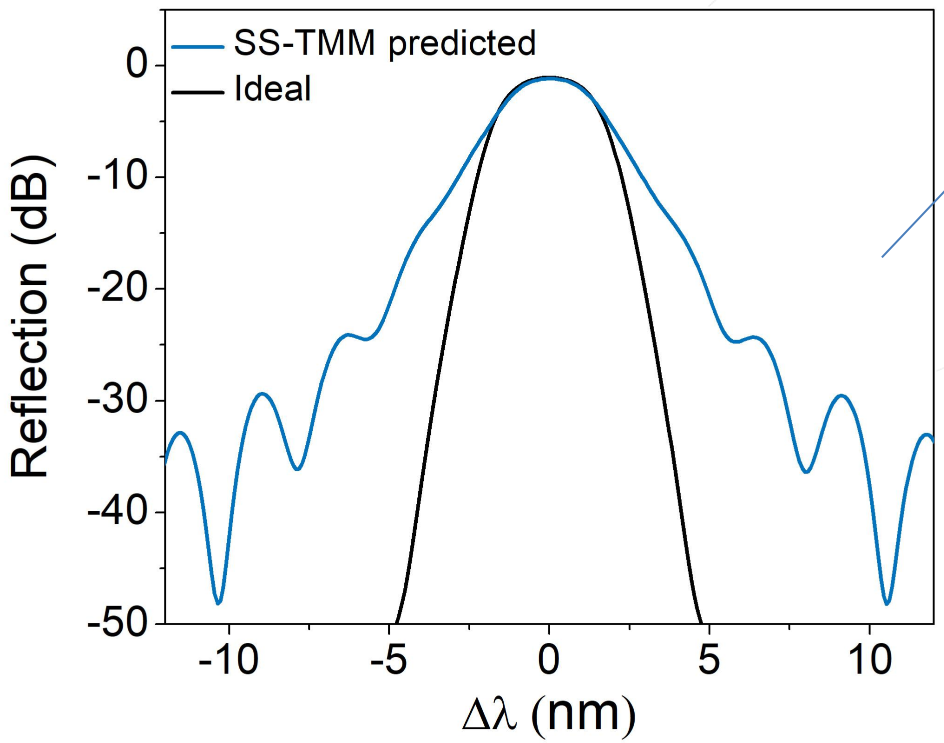
- APN: apodization phase noise
  - apodization in IBGs is typically accompanied by unwanted effective index variations Δn_{eff}
  - Δn_{eff} will act as apodization phase noises, **largely impairing** the response of the apodized IBG





Apodization phase noise (APN) issue

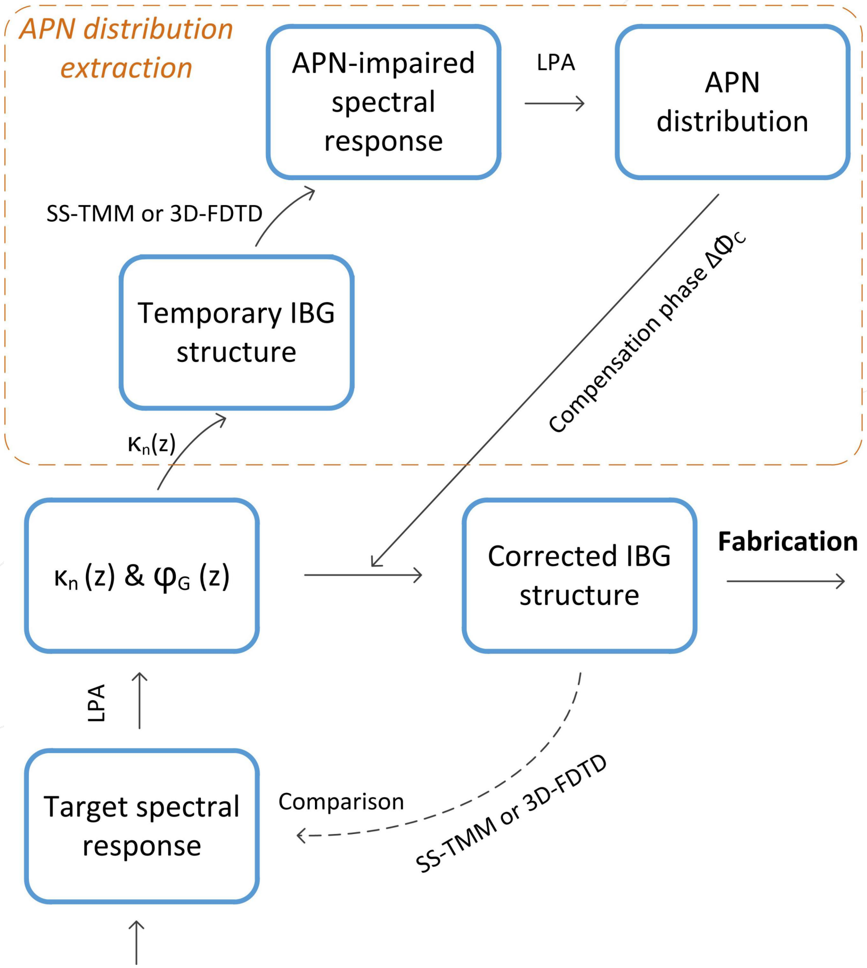
Misalignment-modulated Gaussian-apodized IBG



Spectral broadening due to APN, leading to a chirp effect

APN compensation and spectral correction for apodized silicon IBGs

Diagram flow of the APN compensation process for spectral correction of an apodized IBG

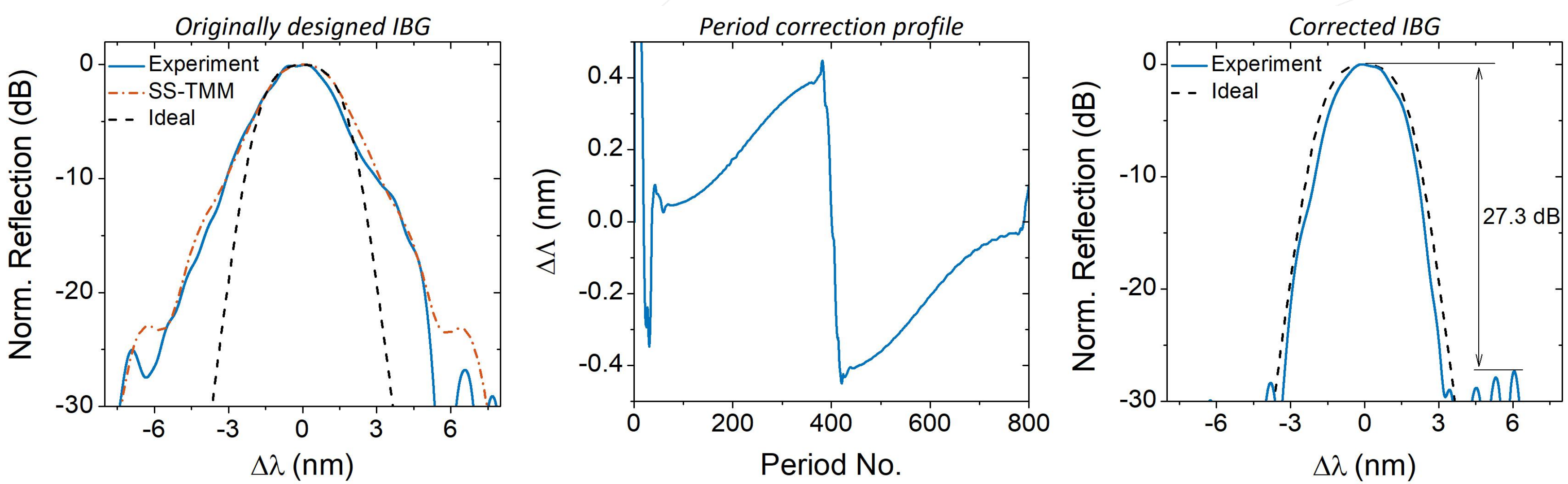


R. Cheng, Y. Han, and L. Chrostowski. Optics Express 27.7 (2019): 9516-9535.

APN compensation of Gaussian-apodized misalignment-modulated silicon IBGs

Experimental results

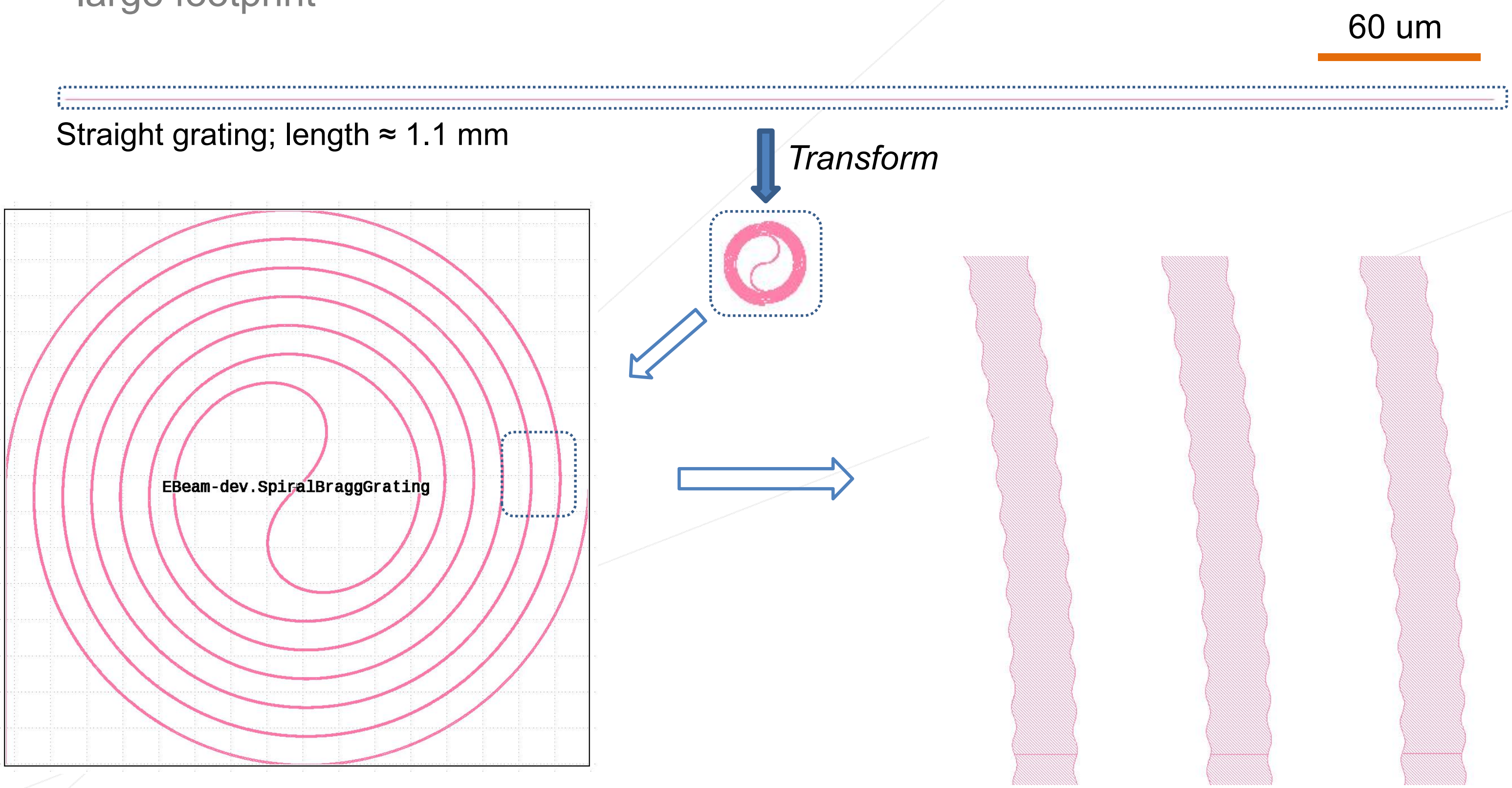
- Original grating
  - significant spectral broadening due to APN
  - the impaired spectrum agrees well with that predicted by the SS-TMM
- Corrected grating
  - much better agreement with the ideal
  - side-lobe suppression ratio is as high as 27.3 dB



R. Cheng, Y. Han, and L. Chrostowski. Optics Express 27.7 (2019): 9516-9535.

Transform long straight grating into spiral shape

- Issues caused by long grating length
  - more subject to chip non-uniformities
  - fabrication stitching errors
  - large footprint



Available in SiEPIC Klayout Library