Sampled, Super-structured Multi-channel FBG

Sampling (periodic superstructure) of FBG generates multiple copies (channels) of the frequency response

FBG pattern n(z) = n_0 + (Δn/2) cos(2πz/Λ + φ) (space domain)

rect' sampling pattern S(z) (space domain)

Sampled FBG = n(z)•S(z)

Sampled FBG response (frequency or wavelength domain)

Each peak represents a response channel

Sinc’ sampling enables a flat spectral response

FBG pattern n(z) = n_0 + (Δn/2) cos(2πz/Λ + φ) (space domain)

'Sinc' sampling pattern S(z) (space domain)

Sinc Sampled FBG = n(z)•S(z)

Sampled FBG response (frequency or wavelength domain)

Uniform 'rect' envelope of the frequency response is a result of the Fourier Transform of the sinc sampling function (demonstrated by Ibsen et al)
‘Sampling’ of a Fiber Bragg Grating Based on Fourier Analysis

\[ \text{FBG pattern} n(z) = n_0 + \frac{\Delta n}{2} \cos(2\pi z / \Lambda + \phi(z)) \] (space domain)

Phase sampled FBG = \( n(z) \cdot S(z) \) (space domain)

Phase sampled FBG response (frequency or wavelength domain)

No ‘wasted’ fiber with phase sampling

Design of 7-15 channel FBGs

Near field diffraction of a phase-shifted phase mask

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2. Northrop Grumman, Redondo Beach, CA 90278, USA
Near field of the Phase mask for writing FBG

Motivation
1. Modeling diffraction near field of a Phase Mask
2. Impact on FBG performance
3. Novel phase masks

Phase shifts in phase mask and in FBGs
Phase shifts in the FBG allows complex-valued coupling coefficients, results in more functionalities and better performance

Applications
- Multi-channel DFB lasers
- Phase-shifted FBG
- Phase-only Multi-channel sampled FBG

Traditional Method:
Fabricate the same phase shift in the phase mask ??
Pattern Transfer in interference lithography
R. Kashyap “Fiber Bragg gratings”, Chap. 6 (Academic, 1999)

Phase-Only Sampled Multichannel FBGs

Near field diffraction after a phase shift
A phase shift is not replicated in FBG, but is split up into two half-phase shift in FBG.

Rigorous vectorial FDTD analysis
Analyzing the fringe Phase distribution, instead of Intensity distribution
Split of the phase shift

Most authors were interested in intensity distribution in the near field. We measure the periods of the fringes in the near field diffraction averaged pattern at different z, along x. Among all the periods of 500 nm there are two periods of 600 nm indicating the phase shift of 250 nm is split to two phase shifts of 125 nm. The separation of the 2 half phase shifts is \( \Delta \theta = \frac{z \tan \theta}{\lambda} \).

Asymmetry of Dammann Sampling function by the split of phase shift

Phase shifts and optical paths are accumulated as the signal propagates along the FBG.

Computed FT of the sampled function with two-split half phase shifts of a separation \( \Delta \phi \) proportional to the phase mask-fiber spacing z.

Experimental spectrum of a sampled FBG
Rolling-off error in multichannel FBG

Measured spectrum
Computed with Phase shift split model

Experimental spectrum of a sampled FBG
A phase shift of \( \pi \) (for FBG) in the phase mask is implemented by introducing a gap of 250 nm in the phase mask, resulting in a groove of 750 nm.

A Dammann sampling function contains a sequence of phase shifts, which are implemented by a sequence of 750 nm in each period of 1 mm.

We change the sequence of \( \pi, \pi, \pi, \ldots \) by the same sequence but of \( \pi, -\pi, -\pi, \ldots \).

Phase shift of \( -\pi \) is implemented by groove of 250 nm.

That does not change the Dammann function.

With the phase shifts split up, the Dammann sampling function in the FBG becomes:

\[ \pi/2, \pi, \pi/2, 0, \ldots \]

Spectral asymmetry is removed.

The sampling function produces channels of equal strength.

Experimental Results

Sampling function with compensation for phase shift splits.

Fabricated 9 channel FBGs.

Conclusion

• Phase shifts in a phase mask used for writing FBGs are not replicated in the fiber core, but split into two half-magnitude phase shifts with a longitudinal separation proportional to phase mask to fiber spacing.
• This split causes asymmetry in the channel spectrum of an FBG
• We built a phase-shift split model which predicts precisely the spectral asymmetry observed in a phase-only sampled FBG.
• This fundamental understanding in the near field is valuable for all the phase-shifted phase masks for a variety of FBGs
• A compensation technique is proposed which produces multi-channel sampled FBGs of high channel count with equal channel amplitudes, and no asymmetry.

PHASE SHIFT DIFFRACTION

Distance between phase mask and the fiber core = d = 62.5 μm

FBGs

ANALYZING RANGE

Near field or Fresnel field
Far field or Fraunhofer field
The boundary between near and far field is defined by Rayleigh distance as:
D = 2L^2/λ, from the source.

Interesting field: d ≈ 62.5 μm
Near field diffraction

DISCRETIZATION OF MAXWELL’S EQUATIONS

Maxwell’s Equations
\[
\frac{\partial B}{\partial t} = -\nabla \times E - J_w \quad \text{(Faraday)}
\]
\[
\frac{\partial D}{\partial t} = \nabla \times H - \tilde{J}_e \quad \text{(Ampere)}
\]
\[
\nabla \cdot H = \rho \quad \text{(Gauss)}
\]
\[
\nabla \cdot B = \mu_0 \rho \quad \text{(Gauss)}
\]

• Linear, isotropic, nondispersive material \( \vec{\epsilon} = \text{const.} \), \( \vec{\mu} = \mu_0 \vec{I} \)
• Electric and Magnetic Current Densities (lossless):
\( \vec{J}_w = \rho \vec{H}, \vec{J}_e = \sigma \vec{E} \)

Yee Algorithm

2nd order central differences in time and space on staggered Cartesian grids.
**ADVANTAGES & DISADVANTAGES OF FDTD**

- **Advantages**
  - Explicit and simple scheme
  - Avoids solving simultaneous equations
  - Fully vectorial without further approximations
  - Time evolution is computed directly
  - Transient is computed directly
  - Provides for complexities of structure shape and material composition

- **Disadvantages**
  - Considerable computer memory
  - Only give numerical results, no physical interpretations

**RESULT**

- Field intensity distribution
- Boundary condition
  - Periodic boundary condition can simulate infinite length but is not available when phase mask has phase shift

**EXTEND WIDTH**

- Extends width
- Integral with other method
  - $\theta \approx 14^\circ$; for $d \geq 62.5 \mu m$, $L_{\text{width}} \geq 40 \mu m$
  - For this dimension, FDTD method needs too big memory
  - After phase mask, only free space propagation
  - Propagation can be computed by easier method
DATA TRANSFORM

- Incident: Gaussian Impulsive wideband electromagnetic excitation
  
  \[ f(t) = \exp\left(\frac{-3\tau^2}{t^2}\right) \sin[2\pi(t - 3\tau)] \]

- Time Domain FT:
  
  \[ F(\omega) = \mathcal{F}\{f(t)\} = \int_{-\infty}^{\infty} f(t) \exp(-j2\pi\omega t) dt \]

- Spatial Filter:
  
  \[ T(\omega) = \mathcal{F}\{H(\omega)\} = \exp\left(\frac{j2\pi}{\Lambda} \sqrt{\omega^2 - \omega_0^2}\right) \]

- Gaussin spectrum in frequency domain

FDTD INTEGRAL FFT

- Indensity pattern

\[ \Lambda_{pm} = 1.0 \mu m, L_{width} = 16 \mu m, \lambda_0 = 250nm, \delta = 250nm, dx = 12.5nm \]

IDEAL CONDITION

- Interference fringe pattern of phase mask can be described as:

  \[ \exp[2\pi((x - x_i)/\Lambda + y \cos \theta / \lambda)] \]

  \[ \exp[2\pi(-(x - x_i)/\Lambda + y \cos \theta / \lambda)] \]

  \[ 1 + \cos(2\pi(x - x_i)/(\Lambda/2)) \]

COMBINE DIFFRACTED FIELDS

- Conventional mask

- \(\Lambda/4\) Phase shifting propagation

- Conventional mask

- Phase-shifted phase mask
COMBINE FRINGE SYSTEMS

Field A: $1+2 = 1 + \cos 2\pi \left( x - \frac{\delta}{2} \right) \frac{A}{L}$

Field B: $2+3 = e^{i2\pi \left( x - \frac{\delta}{2} \right)} \frac{A}{L}$

Field C: $3+4 = 1 + \cos 2\pi \left( x - \frac{\delta}{2} \right) \frac{A}{L}$

RESULT

Phase shift in phase mask splits into two half-amplitude phase shifts
Two half-amplitude phase shifts occur at the boundaries of the three fringe systems
The split of the phase shift is the two interference between two diffracted beams from the two grating sections separated by the phase step $\delta$.

NUMERICAL RESULT

<table>
<thead>
<tr>
<th>Period</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interference period $= \frac{\lambda}{2} = 500\text{nm}$</td>
</tr>
<tr>
<td></td>
<td>At the boundaries, phase shifts in 3.5 periods, total phase shift of: $37.5 \times 50 + 25 = 125\text{nm} = \frac{\delta}{2}$</td>
</tr>
<tr>
<td></td>
<td>Two half phase shifts are not yet completely split</td>
</tr>
</tbody>
</table>

MULTIPLE PHASE SHIFTS

Interference period $= \frac{\lambda}{2} = 500\text{nm}$
At the boundaries, phase shifts in 7 periods, total phase shift of:
- $-12.5 \times 5 = -25 = 125\text{nm} = \frac{\delta}{2}$
- In the central, interference periods are non-influenced, two half phase shifts are split
MULTIPLE PHASE SHIFTS

- Multiple phase shifts in phase mask are split and propagated individually whatever the spacing between the neighboring phase shifts.
- The split half-amplitude phase shifts can cross over during the propagation without changing their values.

Λ_{pm} = 1.0 \mu m, L_{width} = 20 \mu m, d = 10 \mu m, \lambda_0 = 250 nm, \delta = 250 nm, \gamma = 250 nm, \delta x = 12.5 nm

CONCLUSION

- The phase shift in phase mask is not replicated in FBG fiber core
- Ideally, a phase shift in a periodic phase mask will produce three interference fringe systems in the diffraction field.
- The width the third fringe system \( \Delta x = 2 \gamma \tan \theta \), depends on the propagation distance \( y \) from the phase mask to the fiber core.
- Two half-amplitude phase shifts occur at the boundaries of the three fringe systems.

Broadband Fixed Dispersion Compensator

- Core Technology: high-channel-count Fiber Bragg Gratings

max IL ripple in ch (+/-) = 0.22 dB
IL non-uniformity (+/-) = 0.46 dB
GDR spec p-p = 29.30 ps

80 km dispersion compensator
Limitations for the sampling methods

• Sampling approaches are based on the resonant coupling theory, it can explain the mechanism of the multiple channel formation, but cannot provide accurate solution of the channel itself, which will inevitably make the intra-channel spectrum non-ideal.

• The periodic sampling method is inherently suitable to design a multi-channel FBG with identical channel-channel response and constant channel spacing. It fails if the complex spectrum of each channel or the channel spacing needs to be considerably different.

Inverse Scattering Algorithms for the Synthesis of Bragg Gratings

OUTLINE

• Introduction
• First Born approximation
• Iterative solution of the Gel’fand-Levitan-Marchenko equation
• Layer-peeling algorithm
• Numerical examples
• Conclusions

Introduction

Complex filters (add/drop, gain flattening, dispersion compensator etc.) are required in WDM fiber communication system

• Fabrication of complex grating structure is possible
• Design and synthesis Bragg grating becomes very important

Inverse Scattering(IS) methods:
• First Born approximation
• Integral method
• Differential method -- layer-peeling algorithm

Nonlinear optimization method
• Genetic algorithm
• Slow, search space is huge
• Design more practical grating profile

First Born Approximation

First Born approximation accounts only the first reflection from the media

Fourier transform relation exist between the filter spectrum response \( r(\delta) \) and the grating coupling function \( q(z) \):

\[
q(z/2) = -2FT^{-1}[r(\delta)]
\]

\[
q(z) = -\frac{1}{\pi} \int r^*(\delta) e^{-2i\delta z} d\delta
\]
First Born Approximation

Red curve: target spectrum, Blue curve: reconstructed spectrum
First Born approximation is only valid for design low-reflectivity (<0.5) gratings

Method for Synthesis Fiber Bragg Grating

• Layer peeling algorithm


Inverse scattering problem

• Quantum mechanics inverse scattering problem:

\[ \hbar^2 \frac{d^2 \psi(z, k)}{dz^2} + V(z, k) \psi(z, k) = E \psi(z, k) \]

- State function: \( \psi(z, k) \) 
- Potential: \( V(z, k) \)

• Electromagnetic inverse scattering problem:

\[ \frac{\partial^2 E(z, \tau) \phi^2}{\partial z^2} - \frac{\partial^2}{\partial \tau^2} E(z, \tau) - \frac{\partial}{\partial z} (N(z) E(z, \tau)) \]

- Scattering wave: \( E(z, \tau) \)
- Plasma of electron density: \( N(z) \)

• Synthesis of fiber Bragg grating:

- Reflective spectral: \( H_r(\beta) \)
- Coupled coefficient: \( \beta(\tau) \)

Scattering and propagation matrix for complex FBGs

Scattering matrix:

\[ \mathbf{M}_s(\lambda) \approx \mathrm{cosh}(\beta) \begin{bmatrix} 1 & \frac{\hbar}{2} \tanh(\beta) \\ \frac{\hbar}{2} \tanh(\beta) & 1 \end{bmatrix} \]

Propagation matrix:

\[ \mathbf{M}_p(\Delta) = \lim_{\Delta \to 0} \mathbf{M}_s(\lambda) \begin{bmatrix} e^{\Delta^2} & 0 \\ 0 & e^{-\Delta^2} \end{bmatrix} \]

Complex FBGs

\[ \mathbf{M}_c(\lambda) = \mathbf{M}_s(\lambda) \beta(\lambda) \mathbf{M}_p(\Delta) \beta(\lambda) \]
Skaar’s Layer peeling algorithm

Transform matrix:
\[
\begin{bmatrix}
\cosh(\Delta) & j \frac{\Delta}{2} \\
\frac{\Delta}{2} & \cosh(\Delta)
\end{bmatrix}
\]

\[
\rho = \frac{1}{\pi} \int_{\beta} r(\beta) d\beta
\]

Causality and layer-peeling

\[b_j(0) = H_j(\beta)\]
\[b_j(0) = 1\]
\[b_j(m\Delta) = 0.\]
\[b_j(m\Delta) = H_j(\beta)\]

Procedures of Skaar’s LPA

\[r_j(\beta) = \frac{\Delta}{\pi} \int_{\beta} r(\beta) d\beta\]
\[\rho_j = -\tanh[\frac{\Delta}{2\rho_j}]\]

Time domain Layer peeling algorithm

\[r_j(\beta) = \frac{1}{\pi} \int_{\beta} r(\beta) d\beta\]
\[\rho_j = -\tanh[\frac{\Delta}{2\rho_j}]\]

\[q_j = -(1/\Delta) \arctan(h[\rho_j])\]
Examples 2: Design of 2nm Band-pass Filter

Examples 3: Design of 10nm Band-pass Filter

Conclusion

- Four kinds of LPA are introduced
- Two kinds of Skaar’s LPA are proved
- The theories of Skaar’s LPA need further probe.

Future work
- Synthesis of volume grating by LPA
- Synthesis of multi-channel grating by LPA

Outline

- Introduction
- Iterative layer-peeling Algorithm
- Design WDM bandpass filter
- Conclusion
Refractive index modulation of FBG

Refractive index modulation:
\[ \Delta n(z) = \Delta n(z) \cos \left( \frac{2\pi}{\Lambda} z + \theta(z) \right) \]

Coupling coefficient:
\[ q(z) = -\frac{j \pi \Delta n(z)}{2c} \exp \left[ -j \theta(z) \right] \]

Analysis and Synthesis of FBG

Continuous Layer-peeling algorithm (1)

Coupled-mode equations
\[ \frac{\partial \psi(z, \beta)}{\partial z} = j \left[ \Delta \psi(z, \beta) + q(z) \psi(z, \beta) \right] \]
\[ \frac{\partial \psi(z, \beta)}{\partial z} = -j \left[ k(z, \beta) + \dot{q}(z) \right] \psi(z, \beta) \]

Reflection spectrum: \[ r(\beta) = \frac{r(0, \beta)}{u(0, \beta)} \]
Local reflectivity: \[ r(z, \beta) = \frac{r(\Lambda, \beta)}{u(z, \beta)} \]

Synthesis relation:
\[ q(z) = \frac{1}{\pi} \int r(z, \beta) \, d\beta \]

Continuous Layer-peeling algorithm (2)

Synthesis
\[ q(0) = -2 \int r(\beta) \frac{df(\beta)}{df} \]
\[ r(0, \beta) = \frac{2 \int r(\beta) df(\beta)}{\pi \Delta} \]

Analysis
\[ q(z) = \frac{2 \int r(z, \beta) df(\beta) - q(z) r(z, \beta)^2 + q^*(z)}{2} \]
\[ r(L, \beta) = 0 \]

Runge-Kutta method
Discrete layer-peeling algorithm (1)

Transform matrix:
\[
\begin{bmatrix}
\cosh(\Delta) - \frac{\Delta}{2} \sinh(\Delta) & \frac{\Delta}{2} \sinh(\Delta) \\
\frac{\Delta}{2} \sinh(\Delta) & \cosh(\Delta) + \frac{\Delta}{2} \sinh(\Delta)
\end{bmatrix}
\]

\[
\begin{align*}
\alpha(\beta, \rho) = & \frac{1}{\sqrt{1 - \rho^2}} \begin{bmatrix}
\cosh(\Delta) - \frac{\Delta}{2} \sinh(\Delta) & \frac{\Delta}{2} \sinh(\Delta) \\
\frac{\Delta}{2} \sinh(\Delta) & \cosh(\Delta) + \frac{\Delta}{2} \sinh(\Delta)
\end{bmatrix} \begin{bmatrix}
\alpha(\beta, \rho) \\
\alpha(\beta, \rho)
\end{bmatrix} \\
\rho = & -\text{tan}^{-1}\left(\frac{\Delta}{\pi}\right)
\end{align*}
\]

\[
\tau(\beta) = e^{-\beta \alpha} \frac{\alpha(\rho) - \rho}{1 - \rho^2 \alpha(\rho)}
\]

Methods for Design Fiber Bragg grating

- Optimal method:
  - Variation
  - Annealing algorithm
  - Genetic algorithm

- Iterative layer peeling algorithm

Discrete Layer-peeling algorithm (2)

\[
\begin{align*}
\rho & = \frac{\pi}{2} \frac{\pi}{\beta \rho} \\
r(0, \beta) & \xrightarrow{\text{FFT}} q(0) \\
r(\Delta, \beta) & \xrightarrow{\text{FFT}} q\left(\frac{\alpha}{\Delta}\right)
\end{align*}
\]

Analysis:

\[
\begin{align*}
q(z) & = e^{i\pi \rho} \frac{r(z) - \rho}{1 - \rho \rho} \\
r(L, \beta) & = 0
\end{align*}
\]

Iterative layer-peeling algorithm

- Synthesizing by LPA
- Analyzing by ILPA
The convergence of Iterative LPA

- The nonlinear property of LPA becoming approximate linear
- Providing a high number of degree of freedom
- Small modifying grating and spectrum in each iteration

Modified Fourier Transform Method

\[
\frac{d^2L(z, \beta)}{d\beta^2} = q(z) - q(z)^* \tanh(z) - j \beta L(z, \beta) \quad \text{if } q \text{ is real}
\]

\[
\frac{d^2L(z, \beta)}{d\beta^2} = -\frac{1}{\pi} \int_{-\infty}^{\infty} q(z') e^{-j \beta z'} dz'
\]

Riccati equation

\[
\tan^{-1} r = e^{-j \beta z} \int q(z) e^{-j \beta z} dz
\]

\[
H(z) = r(0, \beta) - \left[ \int q(z) e^{-j \beta z} dz \right] - \left[ -\frac{1}{\pi} \tan^{-1} |H(z)| \right]
\]

\[
q(z) = -2i \left[ \tan^{-1} |H(z)| \exp(-j \beta z) \right] \frac{dH}{dz}
\]

Design example: 100G WDM filter

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Reflectivity</th>
<th>Isolation</th>
<th>Dispersion (ps/nm)</th>
<th>Grating Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1550</td>
<td>0.99</td>
<td>-30 dB</td>
<td>100</td>
<td>300</td>
</tr>
</tbody>
</table>

The specifications of WDM filter

- Flat reflectivity of 0.99 in the signal pass band of 0.4 nm around the center wavelength of 1550 nm.
- Isolation of -30 dB in the out-of-the-band (1550.4 nm and 1549.6 nm)
- Maximum dispersion below 100 ps/nm within the signal pass band.
- The grating contains no phase jump
Methods of removing the phase jump in grating

1. Negative part of grating becoming positive
2. Removing negative parts of grating
3. Decreasing the negative part of grating step by step

Negative part of grating becoming positive

Removing negative parts of grating

Decreasing the negative part of grating step by step
Methods of shorting the grating

- Threshold
- Removing smaller lobes

Smoothing grating

- Smoothing by Welch windows

Smoothing windows

- Windows and their Spectrum
Example of smoothing grating

Scaling grating

Designed Results (Threshold Method)

M = 20    iso = -30.3293    bw05 = 0.4639    BWU = 0.5946    rms = 0.5714    maxdpt = 99.3892

M=40    Iso= -30.1437     bw05=0.3943     BWU=0.5353     rms=0.6392     maxdpt=137.0355

Designed Results (Removing smaller lobs)

<table>
<thead>
<tr>
<th>Lab</th>
<th>Isolation (dB)</th>
<th>0.5 dB Bandwidth (nm)</th>
<th>BWU</th>
<th>GDE (ps)</th>
<th>Dispersion @ -0.5 ps/nm (ps/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-30.0895</td>
<td>0.458</td>
<td>0.7963</td>
<td>2.3964</td>
<td>98.1633</td>
</tr>
<tr>
<td>2</td>
<td>-31.1894</td>
<td>0.480</td>
<td>0.5568</td>
<td>2.6255</td>
<td>96.1367</td>
</tr>
<tr>
<td>3</td>
<td>-30.0520</td>
<td>0.419</td>
<td>0.5643</td>
<td>2.3051</td>
<td>92.6235</td>
</tr>
<tr>
<td>4</td>
<td>-30.0758</td>
<td>0.487</td>
<td>0.5662</td>
<td>2.2776</td>
<td>90.8975</td>
</tr>
<tr>
<td>5</td>
<td>-30.1452</td>
<td>0.508</td>
<td>0.5594</td>
<td>2.2655</td>
<td>95.5861</td>
</tr>
</tbody>
</table>
**Designed Results**

(Removing negative coupling coefficient and smaller lobes)

M = 20  iso = -30.0895  bw05 = 0.4938  BWU = 0.6763  rms = 0.5908  maxdpt = 90.6163

M = 16  iso = -30.0768  bw05 = 0.4076  BWU = 0.5602  rms = 0.2776  maxdpt = 89.9075

**Gaussian and ILPA Apodized FBG**

Gaussian and ILPA Apodized FBG

<table>
<thead>
<tr>
<th>Apodization</th>
<th>Isolation (dB)</th>
<th>-1 dB (nm)</th>
<th>-3 dB (nm)</th>
<th>-5 dB (nm)</th>
<th>-10 dB (nm)</th>
<th>-20 dB (nm)</th>
<th>Deposition on 1 dB gap lumen (nm)</th>
<th>Deposition on 0.5 dB gap lumen (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian II</td>
<td>-29.8754</td>
<td>0.2375</td>
<td>0.4838</td>
<td>0.3778</td>
<td>0.7821</td>
<td>0.3347</td>
<td>91.938</td>
<td>90.078</td>
</tr>
<tr>
<td>Gaussian I</td>
<td>85.6323</td>
<td>0.1254</td>
<td>0.4175</td>
<td>0.4838</td>
<td>1.1167</td>
<td>0.4332</td>
<td>91.192</td>
<td>90.232</td>
</tr>
</tbody>
</table>

**Designed Results**

(Decreasing the negative part of grating step by step)

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Iterative #</th>
<th>Isolation (dB)</th>
<th>-1 dB (nm)</th>
<th>-3 dB (nm)</th>
<th>-5 dB (nm)</th>
<th>-10 dB (nm)</th>
<th>-20 dB (nm)</th>
<th>Deposition on 1 dB gap lumen (nm)</th>
<th>Deposition on 0.5 dB gap lumen (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>25.6292</td>
<td>0.5325</td>
<td>0.6759</td>
<td>0.5763</td>
<td>0.6868</td>
<td>90.5725</td>
<td>90.4265</td>
<td>90.0678</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
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<td>0.6759</td>
<td>0.5763</td>
<td>0.6868</td>
<td>90.5725</td>
<td>90.4265</td>
<td>90.0678</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>25.6292</td>
<td>0.5325</td>
<td>0.6759</td>
<td>0.5763</td>
<td>0.6868</td>
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**Designed Results**

(Decreasing the negative part of grating step by step)

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Iterative #</th>
<th>Isolation (dB)</th>
<th>-1 dB (nm)</th>
<th>-3 dB (nm)</th>
<th>-5 dB (nm)</th>
<th>-10 dB (nm)</th>
<th>-20 dB (nm)</th>
<th>Deposition on 1 dB gap lumen (nm)</th>
<th>Deposition on 0.5 dB gap lumen (nm)</th>
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</table>

**Gaussian and ILPA Apodized FBG**

Gaussian and ILPA Apodized FBG
Designed Results

(Decreasing the negative part of grating step by step)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Relative</th>
<th>Isolation (dB)</th>
<th>0.5 dB BW (nm)</th>
<th>30 dB BW (nm)</th>
<th>3 dB BW (nm)</th>
<th>Group delay (ps)</th>
<th>Dispersion @ 0.5 dB (ps/nm)</th>
<th>The bandwidth of flat-top constraint in spectrum (nm)</th>
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<tr>
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Conclusions

Iterative layer-peeling algorithms were developed

- Convergence condition
- Fabrication constraints
- Design of WDM filter

Future work:

- Designed dispersion compensator

References